

Investigation of High Load Anaerobic Digester Design
Parameters: Effect of Reaction Kinetics on Digester Design
Recommendations

Von der Fakultät 4 Energie-, Verfahrens- und Biotechnik
der Universität Stuttgart zur Erlangung der Würde eines
Doktor Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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To Anaïs and Juno

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Certificate of Authorship

CERTIFICATE OF AUTHORSHIP

I, hereby declare that this submission is the result of my own work and intellectual contribution and to the best of my knowledge and belief, understand that it contains no material previously published or written by another person, except where due quotes have been made in the dissertation. Any contribution made to the research by students that I personally supervised or colleagues with whom I have worked with at the Fraunhofer Institute for Interfacial Engineering and Biotechnology or elsewhere is fully acknowledged.

A handwritten signature in black ink, appearing to read 'B. Waelkens', with a stylized flourish at the end.

Stuttgart, September 30th 2019

Barbara Elisabeth Waelkens

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations	Description
ABNT	Associação Brasileira de Normas Técnica
ADM1	Anaerobic Digestion Model Nr. 1
ANOVA	Analysis of Variance
AM	Acetoclastic Methanogenesis
BOD	Biochemical Oxygen Demand
BMP	Bio-Methane Potential
CHP	Combined Heat and Power Plant
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.
HBu	Butyric Acid
HLD	High Load [Anaerobic] Digestion
HM	Hydrogenotrophic Methanogenesis
HPro	Propionic Acid
HRT	Hydraulic Retention Time
HVa	Valeric Acid
IWA	International Water Association
LCFA	Long Chain Fatty Acids
LHV	Lower Heating Value
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
OLR	Organic Loading Rate
ODE	Ordinary Differential Equation
PBM	Particle Break Up Model
PE	People Equivalent
PS	Primary Sludge

List of Symbols and Abbreviations

Abbreviations	Description
PST	Primary Settling Tank
rQSSA	reverse Quasi-Steady-State-Assumption
SAO	Syntrophic Acetate Oxidation
SOR	Surface Overflow Rate
sQSSA	standard Quasi-Steady-State-Assumption
SRT	Sludge Retention Time
STP	Standard Temperature and Pressure
TiS	Tanks in Series
VFA	Volatile Fatty Acids
WAS	Waste Activated Sludge
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

List of Symbols and Abbreviations

Symbols	Units	Description
A	[mol]	Substrate
A	[m ²]	Area
B	[1]	growth parameter constant for Contois kinetics
bTVS	[% _M]	Biodegradable Total Volatile Solids Fraction
C_i	[g/l] or [mol/l]	Concentration of component "i"
C_M	[g/l]	Michaelis-Menten type kinetic constant
dC_i/dt	[g/(l*d)] or [mol/(l*d)]	rate of change of component "i"
ΔG'	[kJ/mol]	Gibbs free energy
ΔG^{0'}	[kJ/mol]	Gibbs free energy at standard conditions and pH 7 (25°C and 10 ⁵ Pa)
e	[kWh/d]	Electric energy flow
E	[mol]	Enzyme
EA	[mol]	Enzyme Substrate Complex
τ	[d]	Hydraulic Retention Time
k₁	[l/(mol*d)] or [l/(g*d)]	forward rate constant
k₋₁	[1/d]	reverse rate constant
k_{1st}	[1/d]	first order kinetic constant
k₂	[1/d]	catalytic rate constant
k_C	[1/d]	Specific biomass growth rate
k_{Cmax}	[1/d]	Maximum specific biomass growth rate
k_{end}	[1/d]	Endogenous respiration rate
k_{Hyd}	[1/d]	Hydrolysis constant

List of Symbols and Abbreviations

Symbols	Units	Description
K_M	[g/l] or [mol/l]	Michaelis-Menten constant
K_S	[g/l] or [mol/l]	Monod constant
m	[g/h] or [kg/h] or [kg/d]	Mass flow
M	[g] or [kg]	Mass
n		Number of (independent) variables in sample
N_A	[mol]	Moles of component A
η	[%]	Efficiency
P	[mol]	Product
P	[kW]	Power
p	[bar] or [mbar]	Partial pressure
R	[kJ/(mol*K)]	Ideal Gas Constant
r_i	[g/(l*d)] or [mol/(l*d)]	or reaction rate of component "i"
ρ	[kg/m ³]	Density
s*		standard deviation of log normal distribution
σ		intrinsic uncertainty
T	[°C] or [K]	Temperature
t_d	[d]	cell doubling time
τ	[h] or [d]	average hydraulic retention time
TS	[% _M]	Total Solids Fraction
TVS_M	[% _M]	Total Volatile Solids Fraction referenced to sample mass
TVS_{TS}	[% _{TS}]	Total Volatile Solids Fraction referenced to TS
U_i	[%]	Fractional conversion of component "i"

List of Symbols and Abbreviations

Symbols	Units	Description
U_G	[l/kg _{TVS0}]	Biogas production per added organic substrate
v	[m ³ /s] or [m ³ /d] or [m ³ /h]	Volumetric Flow
V	[m ³]	Volume
x		calculated value
x_i		Independent variable
\bar{x}^*		mean of log normal distribution
Y_{C/bTVS}	[g/g]	Yield of biomass from biodegradable total volatile solids
Y_{CA}	[g/g]	Yield of biomass on substrate

List of Symbols and Abbreviations

Subscripts	Description
0	identification of component at initial concentration or inflow
1st	First
A	Substrate
AS	Activate Sludge
AT	Aeration Tank
bCOD	biodegradable Chemical Oxygen Demand
bTVS	biodegradable Total Volatile Solids
C	Cells or Biomass
CA	Cell Substrate Complex
COD	Chemical Oxygen Demand
cTVS	Cells as total volatile solids
D	Digester
DS	Digested Sludge
E	Enzyme
EA	Enzyme Substrate Complex
el	Electric
d	Doubling time
G	Gas
i	identification of component
in	Input
l	liquid
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
N	Number of reactors
out	Output
P	Product

List of Symbols and Abbreviations

Subscripts	Description
PE	People Equivalent
PS	Primary Sludge
PST	Primary Settling Tank
R	Recalcitrant
RS	Raw Sludge
RTVS	Recalcitrant total volatile solids
STP	Standard Temperature and Pressure
TS	Total Solids
TVS	Total Volatile Solids
tot	Total
V	Volumetric
WAS	Waste Activated Sludge
w	water
ww	wastewater

ABSTRACT

Anaerobic digestion is one essential part of the treatment process of wastewater sludge. It reduces and stabilizes particulate and dissolved organic material, decreases odor and produces energy. The relevance of the anaerobic digestion process has been clearly established. However, the design of anaerobic digesters can still be improved. Today, engineering design recommendations for anaerobic digesters are based on empirical approaches or first order kinetics. These approaches present some limitations: they do not describe the performance of digesters under high load conditions and low hydraulic retention times, they do not support the designing engineer to predict washout situations and they do not accurately describe the performance of two tanks in series. This thesis shows that simple Michaelis-Menten type kinetics are better suited for wastewater sludge digester design, as is demonstrated with data from full-scale anaerobic digesters.

The presented results were obtained from the operational data books of 12 full-scale anaerobic digestion systems installed on wastewater treatment plants (WWTPs), four digestion systems are high load anaerobic digesters and eight are conventional anaerobic digesters. Overall, a total of more than 40 years of operational data and 18 distinct operational steady settings were analyzed.

The hydraulic retention time of the 18 evaluated operational settings ranged between 5 and 85 days. The organic loading rate ranged between $0.3 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ and $6.9 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$. The analyzed digesters presented a range of total solids concentration at the inflow between 2 % and 9 % and a solids composition that is influenced by primary and waste activated sludge. The effectiveness of the total volatile solids (TVS) removal was evaluated through the determination of the TVS stabilization fraction (47 % to 68 %) and specific biogas production per organic substrate added ($209 \text{ l/kg}_{\text{TVSAd}}$

Abstract

– 732 l/kg_{TVSAd}). The reactor efficiency was determined through the total solids removal rate [0.2 kg/(m³*d) – 3.2 kg/(m³*d)] and the specific biogas production rate [0.149 m³/(m³*d) – 3.404 m³/(m³*d)].

Two kinetic models were evaluated to describe the anaerobic digestion process: the conventional first order kinetic model (0.2 1/d ≤ k_{1st} ≤ 10 1/d) and a kinetic model based on Michaelis-Menten type kinetics (1 g/l ≤ C_M ≤ 10 g/l; 0.12 1/d ≤ k_{Cmax} ≤ 0.60 1/d). The relevant kinetic constants were selected from data reported in literature and adjusted within this range. A sensitivity analysis was executed to investigate the relevance of the kinetic and process parameters. Within the evaluated range, digester performance was most affected by biodegradability and specific biomass growth rate k_{Cmax}.

Typical anaerobic digester design based on 1st order kinetics was compared to Michaelis-Menten type kinetics and overlapped with the results from the analyzed WWTPs. It was possible to show that at higher hydraulic retention times over 20 days, first order kinetics and Michaelis-Menten type kinetics can be used interchangeably. At lower hydraulic retention times Michaelis-Menten type kinetics presented more accurate performance predictions. It was possible to: describe digester performance under high organic loading rates and low hydraulic retention times, predict the washout point and predict the performance of two digesters in series.

The possibility of considering maximum reaction rates and washout phenomena, combined with a good level of accuracy allow an expanded understanding of the optimization potential of an anaerobic digester. The behavior of the high load digester, two digesters in series and the effects of recuperative thickening can be described better through the single rate Michaelis-Menten type kinetics. As a result, improvements can be deduced and the design and control of digesters expanded.

ZUSAMMENFASSUNG

Die anaerobe Vergärung oder Faulung ist ein wesentlicher Bestandteil der Klärschlammbehandlung. Dieser Prozess reduziert und stabilisiert partikuläre und gelöste organische Substanzen, reduziert Gerüche und erzeugt Energie. Die Relevanz des Faulungsprozesses ist eindeutig, jedoch kann das Design von Faulbehältern noch verbessert werden. Heute basieren Auslegungsempfehlungen für Faulbehälter auf empirischen Ansätzen oder Kinetiken erster Ordnung. Diese Ansätze weisen einige Einschränkungen auf: Sie beschreiben nicht die Leistung von Faulbehältern unter Hochlastbedingungen und niedrigen hydraulischen Verweilzeiten, sie unterstützen den Konstrukteur nicht bei der Vorhersage von Auswaschsituationen und sie beschreiben nicht genau die Leistung von zwei in Reihe geschalteten Reaktoren. Diese Arbeit zeigt, dass eine einfache Michaelis-Menten-Typ Kinetik für die Auslegung von Faulbehältern auf Kläranlagen geeigneter ist, wie die Auswertung von Daten anaerober Faulbehälter zeigt.

Die vorgestellten Ergebnisse wurden aus den Betriebstagebüchern von 12 anaeroben Faulbehältern auf Kläranlagen ermittelt. Vier Faulbehälter werden als Hochlastfaulungen betrieben und acht Faulbehälter werden als typische Faulungen betrieben. Insgesamt wurden mehr als 40 Jahre Betriebsdaten und 18 verschiedene betriebliche Einstellungen analysiert.

Die hydraulische Verweilzeit der 18 ausgewerteten Betriebseinstellungen lag zwischen 5 und 85 Tagen. Die organische Raumbelastung lag zwischen $0,3 \text{ kg}_{\text{oTR}}/(\text{m}^3 \cdot \text{d})$ und $6,9 \text{ kg}_{\text{oTR}}/(\text{m}^3 \cdot \text{d})$. Die analysierten Faulbehälter wiesen eine Feststoffkonzentration zwischen 2% TS und 9% TS im Zulauf und eine Feststoffzusammensetzung auf, die durch Primär- und Überschussschlamm beeinflusst wird. Der Umsatz des organischen Trockenrückstands (oTR) (47% bis 68%) und die spezifische

Zusammenfassung

Biogasproduktion pro zugeführtes organisches Substrat ($209 \text{ l/kg}_{\text{OTRAD}}$ - $732 \text{ l/kg}_{\text{OTRAD}}$) wurden bestimmt. Der Reaktorwirkungsgrad wurde durch die Gesamtfeststoffentfernungsraten [$0,2 \text{ kg}/(\text{m}^3 \cdot \text{d})$ - $3,2 \text{ kg}/(\text{m}^3 \cdot \text{d})$] und die spezifische Biogasproduktionsrate [$0,15 \text{ m}^3/(\text{m}^3 \cdot \text{d})$ - $3,4 \text{ m}^3/(\text{m}^3 \cdot \text{d})$] ermittelt.

Zur Beschreibung der anaeroben Vergärung wurden zwei kinetische Modelle evaluiert: das klassische kinetische Modell erster Ordnung ($0,2 \text{ 1/d} \leq k_{1st} \leq 10 \text{ 1/d}$) und ein kinetisches Modell auf der Basis der Michaelis-Menten-Kinetik ($1 \text{ g/l} \leq C_M \leq 10 \text{ g/l}$; $0,12 \text{ 1/d} \leq k_{C_{max}} \leq 0,60 \text{ 1/d}$). Die relevanten kinetischen Konstanten wurden aus der Literatur ausgewählt und innerhalb dieses Bereichs angepasst. Eine Sensitivitätsanalyse wurde durchgeführt, um die Relevanz der kinetischen und Prozessparameter zu untersuchen. Innerhalb des untersuchten Bereichs wurde die Leistung des Reaktors am stärksten von der biologischen Abbaubarkeit und der spezifischen Biomassewachstumsrate $k_{C_{max}}$ beeinflusst.

Ein typisches Faulbehälter Design basierend auf der Kinetik erster Ordnung wurde mit einer Michaelis-Menten-Typ Kinetik und mit den Ergebnissen der analysierten Kläranlagen verglichen. Es konnte gezeigt werden, dass bei höheren hydraulischen Verweilzeiten über 20 Tagen, die Kinetik erster Ordnung und Michaelis-Menten-Typ Kinetik beide gleichwertig eingesetzt werden können. Bei niedrigeren Verweilzeiten zeigten Michaelis-Menten-Typ-Kinetiken genauere Vorhersagen. Es war möglich: die Leistungsfähigkeit des Faulbehälters unter hohen organischen Belastungsraten und niedrigen hydraulischen Verweilzeiten zu beschreiben, den Auswaschpunkt vorherzusagen und die Leistung von zwei Faulbehältern in Serie vorherzusagen.

Die Möglichkeit, maximale Reaktionsraten und Auswaschphänomene zu berücksichtigen, verbunden mit einer guten Genauigkeit, erlaubt ein erweitertes Verständnis des

Zusammenfassung

Optimierungspotentials eines Faulbehälters. Das Verhalten der Hochlastfaulung, zwei hintereinandergeschalteter Faulbehälter und der Schlammrückhaltung lassen sich durch eine Michaelis-Menten-Kinetik genauer beschreiben. Dadurch können Optimierungen abgeleitet und die Auslegung und Steuerung von Faulbehältern erweitert werden.

1. INTRODUCTION

Anaerobic digestion is an essential part of the treatment process of organic residues on our planet. *“It is estimated that anaerobic digestion is responsible for the complete mineralization of 5 % to 10 % of all the organic matter available on the earth”* (SPERLING; CHERNICHARO, 2005). The microbial anaerobic digestion has the property of transforming organic material into an energy rich gas and a significantly smaller amount of mineralized solids in the absence of oxygen (MCCARTY, 1964). The process reduces and stabilizes particulate and dissolved organic waste and decreases odor. Production of biogas provides a versatile carrier of renewable energy, as methane can be used to replace fossil fuels in both heat and power generation, as well as vehicle fuel (WEILAND, 2010). Currently landfills, wastewater treatment plants (WWTPs) and bio-energy companies rely on anaerobic decomposition as one of their unit processes. Anaerobic digestion is of increasing interest to reduce greenhouse gas emissions and to facilitate the sustainable development of energy supply. Arguably, it is one of the most promising treatment systems for meeting an environmentally sustainable development (SHOW; TAY; HUNG, 2010).

Anaerobic decomposition of wastewater was first made popular by the Imhoff tank (or Emscher Brunnen) in the early 20th century, with a Patent dating back to 1906. Here, wastewater and sludge were

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effectively separated, resulting in significant anaerobic decomposition of sludge at acceptable cost. The technology gradually developed, eventually resulting in separate anaerobic sludge treatment. (SEYFRIED, 2015).

With the aerobic activated sludge process gaining traction in the 1940s (WEF, 2009), wastewater treatment shifted to the faster, but more energy intensive, aerobic degradation process. Anaerobic digestion was maintained as treatment for the solid phase on large plants, mainly due to its mass reducing properties. Small WWTPs were equipped with prolonged aeration systems. Thus, in Germany, small WWTPs, designed as prolonged aeration systems, stabilize the small amounts of sludge aerobically through increased sludge age. Up until the 1990s, engineers were trained to design simultaneous aerobic sludge stabilization for WWTPs of up to 20.000 people equivalent (PE), only starting to consider anaerobic digestion as an option for WWTPs with more than 30.000 PE. High investment cost for digester construction, combined with low energy costs and cheap sludge disposal options in agriculture favored this approach.

The use of biogas for energy production became relevant again with the incentives to produce renewable energy. New digester design options, as well as an increase in energy and sludge disposal costs resulted in a shift of these process recommendations. Currently, WWTPs as small as 10.000 PE are considering anaerobic sludge stabilization. An important question is, if it is economically [and

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environmentally] sensible to adapt a WWTP with a prolonged aeration system to anaerobic sludge digestion. (GRETZSCHEL et al., 2012).

On the other hand, larger WWTPs combined the activated sludge process for the treatment of the liquid phase and anaerobic digestion to treat the solid rich sludge phase. Most of the existing anaerobic digesters in Germany have been operating for over 25 years, sometimes presenting structural issues or re-sizing demand (KNERR et al., 2017). In addition, several of the existing anaerobic digesters are significantly oversized (WAELEKENS; QUINTANA, 2017).

At the time most of the anaerobic digesters in Germany were designed, accurate and robust reaction kinetic models for anaerobic digestion were not yet available for the design engineer. Only more recently digester design based on kinetic models were established (BATSTONE et al., 2002; DWA, 2014; HEINDL; ROEDIGER, 2016; SIEGRIST et al., 2002). Oversizing of old digesters originated on the one hand by unpredictable factors, such as population development, and on the other hand by uncertainties in estimating digester design and performance, combined with generous safety factors. Up until the mid-2000s, most anaerobic digesters were designed based on empirical guidelines (ATV-DVWK, 2003; METCALF & EDDY, 2004). Now, with more in depth understanding of the anaerobic digestion process and available process models, the design engineer is confronted with new tools to support her decision between selecting

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to renew an existing digester, retrofit it with new technology or re-design the system completely.

Construction of new, smaller anaerobic digesters, as well as the revision of the existing aging infrastructure presents a chance to update anaerobic digester design, based on validated process models. This opportunity should not be wasted.

The first motivator to re-think anaerobic digester design is rooted on simple capital investment. Can a digester be smaller without compromising performance? Will this make anaerobic digesters on smaller WWTPs more viable? Furthermore, two operational drivers motivate re-design of anaerobic digestion on WWTPs: 1) energy consumption is one of the largest cost factors on WWTPs. Prolonged aeration processes are more energy consuming than the combination of activated sludge process and anaerobic sludge digestion (GRETZSCHEL et al., 2012); 2) the second largest cost factor on WWTPs is sludge disposal. In Germany alone, sludge disposal can represent 15 % to 50 % of the total operation costs (WENDLAND, 2005). Reducing sludge volume and improving anaerobic digester performance should significantly reduce operational costs.

It is uncommon however, that operation on WWTPs actively focuses on sludge treatment. Often, anaerobic digesters receive the produced sludge and transform it into biogas and digestate, with only little monitoring of the sludge composition and quality and digester performance. A task presented to the designers and operators of

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WWTPs, is to shift from this current low quality and performance control to an integrated solution with higher quality targets. To achieve this, deeper insight to the characteristics of each waste stream and a better understanding of which treatment strategies are necessary is in demand. Sludge treatment is one of the least optimized processes on WWTPs and can greatly benefit from design improvements.

One of the challenges of designing anaerobic digestion systems lies in the complexity of the digestion process: a myriad of individual metabolism steps executed by mostly unknown microorganisms, through complex syntrophic connections and different optimal environmental conditions, result in the production of methane and carbon dioxide. The combined work of numerous researchers over several years resulted in the development of complex kinetic models to describe the anaerobic digestion process. (BATSTONE et al. 2002; SIEGRIST et al., 2002)

These models are very thorough, allowing significant insights into the dynamic behavior in digesters and providing details on each single step of the anaerobic degradation process. The complex information contained these models, however, does not translate well to simple design rules (BATSTONE, 2006). The common solution is to fall back on empirical approaches for the design of anaerobic digesters (METCALF & EDDY, 2014) or on pragmatic simple approaches such as

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first order kinetic models (GUJER; ZEHNDER, 1983; KAPP, 1984; DWA, 2014).

A further challenge is the introduction of innovative systems into the relatively conservative market of municipal wastewater treatment (LETTINGA, 2014). Operators and engineering companies can be reluctant to introduce new solutions, often due to high investment costs, typically sourced from taxpayers' money, associated with the responsibility of having to guarantee results. This conundrum often does not incentivize innovation, leading to sub-optimal solutions. Schoberth, 1978, provocatively stated that the use of anaerobic digestion processes on WWTPs presents implemented technology dating back to the 1930's. This holds true today, as mixing technology such as the mechanically stirred draft tube suggested by Prüss in 1926 (SEYFRIED, 2015) is still one of the technologies of choice.¹

An emerging technology for the anaerobic treatment of sludge in WWTPs is the high load anaerobic digestion. This technology, developed for the treatment of sludge from municipal wastewater treatment plants, operates at higher organic loads and significantly shorter hydraulic retention times than regular anaerobic sludge digesters (MERZ et al., 1999). It presents reactors three to four times smaller than conventional digesters resulting in a much smaller footprint on the WWTP, with at least equivalent results to

¹ Granted, just because an idea is old, does not mean it is a bad idea.

Introduction

conventional digesters. This unit process could contribute to improve overloaded WWTPs, or be implemented in WWTPs transitioning from aerobic to anaerobic sludge stabilization in urban areas with limited space availability. Design advantages such as improved mixing technology, decreased sludge heating costs and the automation associated with modern digesters result in lower energy demand, improved solids reduction and high biogas production. Currently, there are at least ten operational high load anaerobic digesters installed in WWTPs in Germany that demonstrate the technology's viability.

However, the current state-of-the-art first-order kinetics process model does not accurately portray the operational conditions observed in high load anaerobic digesters. A critical point is the performance prediction at low hydraulic retention times. The lack of accurate and robust reaction kinetic model for high load digestion (HLD) system brings the declared benefit of these digesters into question, limiting their acceptance. A reaction-engineering model that describes the HLD would lead to further improvement of both the conventional and HLD digestion systems and encourage a larger application of the HLD, helping to identify its advantages and limitations.

This thesis proposes an extension of the current single rate kinetic scheme in the design of anaerobic digesters to include the thus far overlooked reaction kinetics that can describe HLD. The model

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extension will be substantiated by data collected from full-scale plants. The process model investigation should grant new insights into design choices for anaerobic digesters, where its limits lie and which optimization strategies to pursue. With a more accurate single-rate-kinetic approach, the observed properties of the HLD can be incorporated in future digester design. The presented results can contribute to an optimization of anaerobic digesters, especially in dense urban areas, tackling the challenge of managing this waste stream.

2. MOTIVATION

Throughout most of the western world, design of anaerobic digesters for WWTP sludge consolidated in 15 to 20 days hydraulic retention time (HRT), with organic loading rates (OLR) between 1.0 and 5.0 kg/(m³*d) (DICHTL; SCHMELZ, 2015, p. 150; METCALF & EDDY, 2014, p. 1509; DWA, 2014, p. 41). However, in Germany, at least 10 full-scale digesters deviate from the consolidated design recommendations, operating at significantly lower HRTs, between 5 days and 10 days, with organic loading rates reaching more than 5.0 kg/(m³*d). Some design recommendations suggest that at short hydraulic retention times, low overall sludge degradation and bacterial washout can occur; however, full-scale high-load-digesters appear to be performing well.

There are likely two reasons why design recommendations do not encompass high-load-digesters:

- 1) There is only limited experimental data available and practically no information on full-scale digester performance published.

Systematic laboratory and pilot analysis have presented results of digester performance at HRTs as low as 3 days (O'ROURKE, 1968 apud WEF, 2009, p. 25-21; KAPP, 1984; SCHÄFER, 1998; KEMPTER et al. 2000). However, there is no context to the operational reality of the WWTPs. Dichtl and Schmelz (2015), p. 150, point out, that the

Motivation

design parameters suggested in literature are [mostly] oriented on theoretical values of hydraulic retention time and organic loading rate. They argue that, only in very few cases there is a critical evaluation of the actual design parameters, considering the boundary conditions on the existing WWTPs and its consequences on digester design. Pavlostathis and Giraldo-Gomez (1991) argue that the well-defined environment of laboratory and pilot studies might oversimplify the complexity of full-scale systems. Thus, they recommend more research focusing on real-life anaerobic treatment systems.

Only scattered information on the performance of full-scale high-load-digesters is available in literature. Reports describe full-scale experiments over limited time spans (ENGEL, 2002; KEMPTER-REGEL et al., 2003; SCHÄFER; BINIEK; SCHREIBER, 2016) or expected results and start-up performances (KEMPTER-REGEL; TRÖSCH, 2009; STERNAD et al., 2016). There is no **systematic analysis of the operation and performance of full-scale digesters at high load conditions (HRT < 10 d and OLR > 5kg_{TVS}/(m³*d)) available.**

- 2) Design recommendations and kinetic approaches are still developing

Due to its complexity, classic digester design recommendations often determine the performance of anaerobic digesters on experience and measurements, e.g. by assuming 70 % degradation of the volatile solids mass (METCALF & EDDY, 2014, p. 1508). Alternatively, some

Motivation

authors propose simple single rate kinetic approaches, assuming a rate-limiting step. Three main kinetic categories are described:

- a) slow first order type kinetics, indicating there is NO explicit dependence on enzyme/microorganism concentration (DWA, 2014, p. 17, PAVLOSTATHIS; GOSSET, 1986, p. 1527; GUJER; ZEHNDER, 1983, p. 161);
- b) Michaelis-Menten/Monod-type kinetics, suggesting there IS an explicit dependence on enzyme/microorganism concentration (O'ROURKE, 1968 apud GOSSET; BESLER, 1982, pp. 1103; GRAEF; ANDREWS, 1974); or
- c) Surface dependent kinetic models, suggesting particle size is the decisive parameter (VAVILIN; RYTOV; LOKSHINA, 1996; SANDERS et al., 2000).

The proposed kinetic approaches are influenced by the dependence (or not) of biomass concentration and the effect of substrate surface. The mechanistic reasoning suggest either a biomass independent rate-limiting hydrolysis step (first order kinetics or surface oriented kinetics) or a biomass dependent, rate-limiting degradation step (e.g. acetoclastic methanogenesis). There is a large range of hydrolysis constants publicized in literature, first order hydrolysis constants vary between slow (0.1 1/d) and fast (10.0 1/d) (BATSTONE et al., 2002a, p. 47), leaving room to interpretation. This indicates a **demand for further evaluation of boundary conditions focusing on the range and plausibility of the rate-limiting kinetic constants.**

Motivation

Thus, the motivation of this thesis was twofold. It aimed to investigate:

- the actual performance of full-scale anaerobic digesters at short hydraulic retention times and high organic loading rates; and
- Identify which single rate limiting kinetic mechanisms would be most plausible and accurate in describing digesters under high load conditions, considering the influence of the WWTP process.

The results of this investigation should deliver a systematic analysis of the operation and performance of full-scale digesters at high load conditions and clarify the performance range of the high load digester compared to conventional digesters. It will show if or when there is a dependence on digester microorganism concentration. It will propose single-rate kinetics to describe the operational conditions of the high load digester, striving to establish how this would affect digester design. The design engineer will be provided with a streamlined approach and necessary tools to estimate digester sizes and loading rates for digesters under high load conditions. She will also be able to determine which boundary conditions are most critical in the planning process.

3. OBJECTIVES

The objective of this thesis is to evaluate the existing design recommendations and first order kinetic approach to model anaerobic digesters and suggest an expansion of the kinetic model to include Michaelis-Menten type kinetics. It aims to identify if and how a reaction-engineering model based on single rate kinetics can explain the performance observed in the high load anaerobic digester (HLD) and identify recommendations for design improvement. To reach this objective three aims are pursued:

- 1) The first aim is to identify and characterize the design and operational parameters of existing WWTPs equipped with conventional and high-load anaerobic digesters, specifically regarding inflow loads and sludge quality. Sludge decomposition parameters such as sludge reduction efficacy, sludge reduction rate, specific biogas production and biogas production rate are determined. (Chapters 6 and 7)
- 2) The second aim is to evaluate the effect of single rate kinetics over anaerobic digester design and analyze its consequences regarding digester optimization potential, considering the current first order kinetics and alternatively a Michaelis-Menten type kinetics approach. The kinetic models are compared, its advantages, disadvantages,

Objectives

accuracy and mechanistic background of both kinetic models discussed.

- 3) The third aim is to evaluate the quality of single rate digester design model predictions based on results from full-scale anaerobic digesters operating between 5 and 85 days of hydraulic retention time, focusing on characterizing the operational conditions of the high load anaerobic digester. This analysis is executed considering completely mixed reactors, two completely mixed reactors in series and the decoupling of the sludge retention time from the hydraulic retention time, identifying its possibilities and limitations.

The results presented in this thesis should allow the design engineer to predict the performance of the high load digester, decide when it is sensible and interesting to install a high load digester, and which design details to focus on.

4. THEORETICAL BACKGROUND

The theoretical background is composed of four chapters. Chapter 4.1 presents the necessary process engineering background to describe anaerobic digesters operated as continuous stirred tank reactors. It describes relevant mass balances and typical kinetic approaches used in process and bioprocess engineering. Chapter 4.2 presents the anaerobic digestion process, describes the known phases of the anaerobic decomposition reaction chain, presents how this reaction chain is interlinked and describes the current models for its description. The models range from a simple stoichiometric approach to dynamic simulations of several differential equations. The latter ones consolidated in the Anaerobic Digestion Model Nr. 1 (ADM1) (BATSTONE et al., 2002a; BATSTONE et al., 2002b). Chapter 4.3 presents substrate sources for the anaerobic digesters on WWTPs. It describes the activated sludge process and its typical sludge streams. Chapter 4.4 describes the common types of reactors and reactor mixing for conventional anaerobic digesters and presents the current background on high load anaerobic digesters. Furthermore, it presents the current design recommendations for anaerobic digesters such as typical values for hydraulic retention time, organic loading rate and performance prediction equations.

4.1. BASIC MASS BALANCES AND KINETICS

In principle, for reactor design purposes, it is sufficient to apply an unstructured model based on macroscopic variables and an overall

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rate limiting kinetic term. *“In the description of the dynamics of the amount of an extensive quantity and, hence, of the overall dynamics of change of the system, two types of information are needed: the kinetics of transport of substances to the locale of the reaction and of the reaction at the locale of the reaction.”* (ROELS, 1982). Reactions in biologic systems, such as the anaerobic digestion, often take place in continuous stirred tank reactors (CSTR). Four typical kinetic approaches apply, first order kinetics, Michaelis-Menten kinetics, Monod kinetics and Contois kinetics. This chapter describes the basic characteristics of a CSTR in steady state and each of these kinetic approaches, as well as the theoretical background of the Michaelis-Menten type kinetics. The kinetic considerations all assume a non-segregated homogeneous fluid.

4.1.1. CONTINUOUS STIRRED TANK REACTOR (CSTR)

CSTR is one of the ideal flow patterns for reactors described in literature (LEVENSPIEL, 1999). In a CSTR the volumetric inflow is equal to the volumetric outflow ($v_{in} = v_{out}$), the concentration of a component “ C_i ” in the reactor is equally distributed throughout the reactor and therefore is equal to the concentration of “ C_i ” at the outflow of the reactor. Eq. 1 presents the mass balance concerning component “ i ”. Eq. 2 presents the fractional conversion “ U_i ” of the component “ i ”. When a CSTR is in equilibrium, or steady state, there is no variation in the concentration of component “ C_i ” and the reaction rate “ r_i ” can be expressed as a function of concentration and

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hydraulic retention time (Eq. 3). The equations are summarized in Table 1.

Table 1: Continuous Stirred Tank Reactor Equations (adapted from LEVENSPIEL, 1999)

CSTR Equations	
$\frac{dC_i}{dt} = \frac{C_{i0} - C_i}{\tau} \pm r_i$	Eq. 1
$U_i = \frac{C_{i0} - C_i}{C_{i0}}$	Eq. 2
$r_i = \pm \frac{C_{i0} - C_i}{\tau}$	Eq. 3

Where:

dC_i/dt : rate of change of component "i"

C_{i0} : Concentration of component "i" at inflow

C_i : Concentration of component "i" in the reactor and at outflow

τ : Average hydraulic retention time

r_i : Reaction rate of component "i"

U_i : fractional conversion of component "i"

4.1.2. FIRST ORDER KINETICS

First order kinetics are one of the basic kinetics described in literature (LEVENSPIEL, 1999). They describe a linear relation between the reaction rate and the concentration of a component (Eq. 4). This type of reaction rate often relates to monoatomic reactions. In a steady state CSTR, the mass balance for first order kinetics can be rewritten as a function of the concentration of component "i" (Eq. 5). Eq. 6 shows the fractional conversion of component "i" in a CSTR. For N

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tanks in series of the same size, Eq. 7 describes the concentration at the outflow of the Nth tank. Eq. 8 describes the total fractional conversion in N reactors. Table 2 summarizes the first order kinetic equations (adapted from LEVENSPIEL, 1999).

Table 2: First order kinetics equations for CSTR (adapted from LEVENSPIEL, 1999)

First Order CSTR Equations	Eq. Nr.
$r_i = k_{1st} * C_i$	Eq. 4
$C_i = \frac{C_{i0}}{1 + k_{1st} * \tau}$	Eq. 5
$U_i = 1 - \frac{1}{1 + k_{1st} * \tau} = \frac{k_{1st} * \tau}{1 + k_{1st} * \tau}$	Eq. 6
$C_{iN} = \frac{C_{i0}}{(1 + k_{1st} * \tau)^N}$	Eq. 7
$U_{iN} = 1 - \frac{1}{(1 + k_{1st} * \tau)^N}$	Eq. 8

Where:

- r_i : reaction rate of component "i"
- k_{1st} : first order kinetic constant
- C_i : Concentration of component "i" in the reactor and at outflow
- C_{i0} : Concentration of component "i" at inflow of the first reactor
- τ : Average hydraulic retention time
- U_i : Fractional conversion of component "i"
- N : Number of reactors
- C_{iN} : Concentration of component "i" in the reactor N and at its outflow
- U_{iN} : Fractional conversion of component "i" for N reactors

In a system ruled by first order kinetics, the increase in concentration " C_i " will result in a directly proportional increase of the reaction rate " r_i " (Eq. 4). In a CSTR, the final concentration of the component " C_i "

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will be controlled by the kinetic constant " k_{1st} ", the selected average hydraulic retention time " τ " and the initial concentration of the component " C_{i0} " (Eq. 5). The fractional conversion of the component " U_i " will be determined by the kinetic constant " k_{1st} " and by the selected average hydraulic retention time " τ " (Eq. 6). This means, that for a CSTR, the design engineer can select the fractional conversion, independently of the initial substance concentration " C_{i0} ", only taking into account the average hydraulic retention time and kinetic constant. By considering more than one tank in series, it is possible to decrease the concentration of the component " i " at the outflow (Eq. 7) and increase its fractional conversion (Eq. 8).

4.1.3. MICHAELIS-MENTEN KINETICS

Mr. L. Michaelis and Ms. Maud L. Menten in their work "Die Kinetik der Invertinwirkung" of 1913 first described reaction dynamics of enzyme activity, presenting a kinetic approach that considered the effect of substrate and enzymes, as well as the complexation velocity, on the development of a reaction. The Michaelis-Menten kinetics describe the reaction between an enzyme "E" and a substrate "A" to form a complex "EA" and then a product "P", releasing the enzyme "E". In their work, they analyzed the action of the invertase enzyme on sucrose: "*...invertase forms a complex with sucrose that is very labile and decays to free enzyme, glucose and fructose*" (MICHAELIS; MENTEN, 1913). Resulting in the canonical enzymatic reaction presented in Eq. 9.

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Where:

- E: Enzyme
- A: Substrate
- EA: Enzyme Substrate Complex
- P: Product
- k_1 : forward rate constant
- k_{-1} : reverse rate constant
- k_2 : catalytic rate constant

Eq. 10 and Eq. 11 respectively present the resulting reaction velocity (or reaction rate) “ r_A ” and Michaelis-Menten constant “ K_M ” (adapted from MICHAELIS; MENTEN, 1913).

$$r_A = -\frac{k_2 * C_{E0} * C_A}{C_A + K_M} \quad \text{Eq. 10}$$

$$K_M = \frac{k_{-1} + k_2}{k_1} \quad \text{Eq. 11}$$

Where:

- r_A : substrate removal rate or reaction velocity as a function of substrate concentration
- C_A : substrate concentration
- C_{E0} : initial enzyme concentration
- K_M : Michaelis-Menten constant
- k_1 : forward rate constant
- k_{-1} : reverse rate constant
- k_2 : catalytic rate constant

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In a system ruled by Michaelis-Menten kinetics, not only the substrate concentration " C_A ", but also the total enzyme concentration " C_{E0} " will influence the reaction rate.

In a two-page "note on the kinetics of enzyme action", Briggs and Haldane (1925) described the mathematical background that characterizes the Michaelis-Menten kinetic model, establishing the necessary boundary conditions through differential equations. Fundamentally, a negligible concentration of enzyme compared to the concentration of substrate or product is necessary and the reaction for the formation of the complex "EA" is practically in equilibrium with its dissociation reaction. Eventually, Segel and Slemrod (1989) analyzed this hypothesis, known as the standard-Quasi-Steady-State-Assumption (sQSSA), in detail (Chapter 4.1.6).

4.1.4. MONOD KINETICS

Bacterial growth is generally presented as a function of the concentration of organisms or cells " C_C ", its specific growth rate " k_C " and its doubling time, t_d (Eq. 12), assuming " k_C " and " t_d " are constants (HERBERT; ELSWORTH; TELLING, 1956). In this approach, the doubling time is a characteristic of each microorganism and independent of substrate concentration.

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$$\frac{1}{C_C} * r_C = \frac{d(\ln C_C)}{dt} = k_C = \frac{\ln 2}{t_d} \quad \text{Eq. 12}$$

Where:

- C_C : Biomass or cell concentration
- r_C : Biomass or cell growth rate
- k_C : Specific biomass or cell growth rate
- t_d : Biomass or cell doubling time

Similar to the Michaelis-Menten approach, Monod (1949) described a kinetic system attempting to characterize the growth of bacterial cultures. He established a mathematical model that describes a relation between the specific growth rate of microorganisms, the available feed (or substrate) concentration during that growth phase and the concentration of microorganisms. It is an empirical equation based on batch experiments in the Article “The Growth of Bacterial Cultures”. Monod states, “*Relatively simple empirical laws were found to express conveniently the relation between exponential growth rate and concentration of an essential nutrient [...] similar to a Langmuir adsorption isotherm or to the Michaelis-Menten equation*”.

The Monod kinetic function is a hyperbolic equation, where the horizontal asymptote is the maximum specific biomass growth rate ($k_{C_{max}}$) and the Monod constant (K_S) is equivalent to the substrate concentration at half of the maximum specific biomass growth rate (Figure 1). Eq. 13, Eq. 14 and Eq. 15 present the essential expression of the Monod kinetics. It establishes the relation between the concentration of the essential nutrient “ C_A ”, the concentration of

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biomass or cells " C_C ", the biomass growth rate (r_C) and the biomass yield from the essential nutrient (Y_{CA}). The constant yield is a simplification that may be only justified for mixed flow reactors, or for the exponential growth phase of batch reactors (Levenspiel 1999). Eq. 16 shows the consumption rate of the essential nutrient " C_A ".

At high substrate concentration in the reactor ($C_A \gg K_S$) Eq. 13 can be simplified to Eq. 17. In this case, the substrate concentration is excessive and does not limit the specific biomass growth rate. "Pseudo zero order" kinetics with regard to substrate concentration rule this segment of the Monod kinetic. At low substrate concentrations ($K_S \gg C_A$) Eq. 13 can be simplified to Eq. 18, and the specific biomass growth rate will be directly proportional to the substrate concentration, since $k_{C_{max}}$ and K_S are constants. "Pseudo first order" kinetics with regard to substrate concentration describe this segment of the Monod kinetic. Table 3 presents the fundamental Monod kinetic equations. Figure 1 presents both conditions.

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Table 3: Fundamental Monod Kinetic Equations

Fundamental Monod kinetic equations	Eq. Nr.
$k_C = k_{Cmax} * \frac{C_A}{K_S + C_A}$	Eq. 13
$r_C = k_C * C_C$	Eq. 14
$Y_{C/A} = \frac{r_C}{r_A} = \frac{k_C * C_C}{r_A}$	Eq. 15
$r_A = \frac{k_C * C_C}{Y_{CA}}$	Eq. 16
$k_C = k_{Cmax} * \frac{C_A}{C_A} = k_{Cmax}$	Eq. 17
$k_C = k_{Cmax} * \frac{C_A}{K_S}$	Eq. 18

Where:

- k_C : specific biomass growth rate
- k_{Cmax} : maximum specific biomass growth rate
- C_A : Substrate concentration in reactor
- K_S : Monod constant
- r_C : Biomass growth rate
- C_C : Biomass concentration in the reactor
- $Y_{C/A}$: Yield of biomass on substrate
- r_A : Substrate consumption rate

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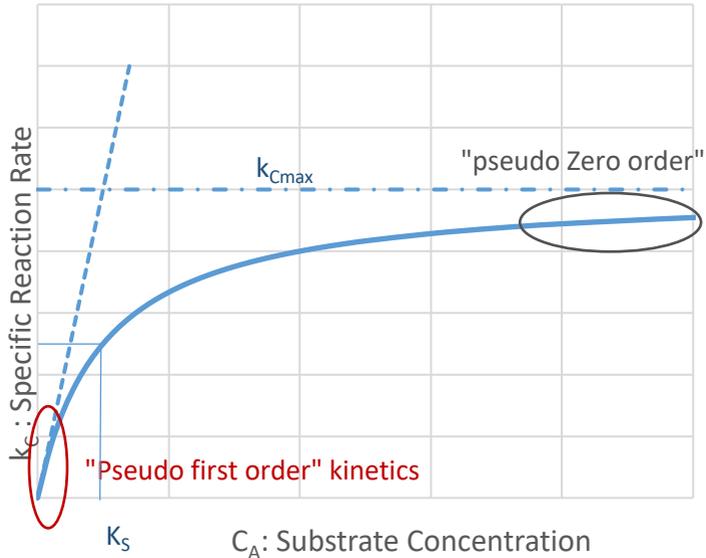


Figure 1: Monod kinetics – specific reaction rate, k_c , as a function of limiting substrate concentration C_A

Assuming a steady state CSTR with no inflow of biomass ($C_{C0} = 0$) it is possible to deduce from the mass balance for biomass, that the specific biomass growth rate is equal to the inverse of the hydraulic retention time ($k_c = 1/\tau$). This allows deriving an equation for the substrate concentration, substituting k_c for $1/\tau$ and solving for C_A . This results in Eq. 19, the substrate concentration in the reactor and at the outflow of a steady state CSTR that operates under Monod Kinetics. It is possible to rewrite Eq. 3 in combination with Eq. 19 to describe the reaction rate of substrate consumption (Eq. 21). Eq. 23 describes the fractional conversion of the substrate. The biomass

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concentration " C_c " (Eq. 20) can be determined by combining Eq. 15 and Eq. 19, and the biomass production rate can be determined through Eq. 22. For an inflow that contains cells and substrate at the inflow ($C_{c0} \neq 0$), Levenspiel (1999) presents the mass balance as presented in Eq. 24. Table 4 presents the summary of the Monod kinetics equations for steady state CSTR.

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Table 4: Summary of Monod kinetics for a steady state CSTR (adapted from LEVENSPIEL, 1999)

Monod CSTR Equations	Eq. Nr.
$C_A = \frac{K_S}{\tau * k_{Cmax} - 1}$	Eq. 19
$C_C = \left(C_{A0} - \frac{K_S}{\tau * k_{Cmax} - 1} \right) * Y_{C/A}$	Eq. 20
$r_A = - \frac{C_{A0} - \frac{K_S}{\tau * k_{Cmax} - 1}}{\tau}$	Eq. 21
$r_C = \frac{\left(C_{A0} - \frac{K_S}{\tau * k_{Cmax} - 1} \right) * Y_{C/A}}{\tau}$	Eq. 22
$U_A = 1 - \frac{K_S}{C_{A0} * (\tau * k_{Cmax} - 1)}$	Eq. 23
$k_{Cmax} * \tau = \frac{(C_{A0} - C_A) * (C_A + K_S)}{\left(\frac{C_{C0} * C_A}{Y_{C/A}} \right) + C_{A0} * (C_{A0} - C_A)}$	Eq. 24

Where:

- C_A : Substrate concentration in reactor
- K_S : Monod Constant
- k_{Cmax} : maximum specific biomass growth rate
- C_{A0} : Substrate concentration at inflow
- τ : Hydraulic retention time
- r_A : Substrate consumption rate
- U_A : Fractional substrate conversion
- C_C : Biomass concentration in the reactor
- $Y_{C/A}$: Yield of Biomass on Substrate
- r_C : Biomass growth rate
- C_{C0} : Biomass Concentration at inflow

In a CSTR, it is possible to describe all relevant reaction equations as a function of the kinetic parameters “ K_S ” and “ k_{Cmax} ”, the average hydraulic retention time “ τ ” and the substrate and biomass

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properties “yield” and “initial concentration”. The substrate concentration in the reactor and at outflow is dependent on the kinetic parameters and the hydraulic retention time, while the reaction rates of substrate and biomass and the conversion of substrate are also directly dependent on the initial substrate concentration at reactor inflow. The biomass concentration is dependent on initial substrate concentration, the biomass yield and the kinetic parameters.

4.1.5. CONTOIS KINETICS

Contois (1959) suggested that the specific growth rate in a continuous culture is a function of the population density and the concentration of the limiting substrate. He pointed out that there has to be a relation between the specific growth rate and the population density. This resulted in an empirical kinetic relation presented in Eq. 25.

$$k_C = k_{Cmax} * \frac{C_A}{C_C * B + C_A} \quad \text{Eq. 25}$$

Where:

- k_C : specific biomass growth rate
- k_{Cmax} : maximum specific biomass growth rate
- C_A : Substrate concentration
- C_C : Biomass concentration
- B : Growth parameter constant

Even though it is empirical in nature, several authors apply the equation presented by Contois to describe the anaerobic digestion

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process (ABATHI et al., 2012; CHEN; HASHIMOTO, 1980; RAMIREZ et al., 2009; VAVILIN et al. 2007).

4.1.6. THE QUASI-STEADY-STATE-ASSUMPTION

Considering the mechanism of Monod kinetics, where substrate and biomass combine to a substrate biomass complex and later form a product, the principle behind Michaelis-Menten kinetics and Monod kinetics is similar. Mathematically both kinetic approaches could be used interchangeable, e.g. if a proportionality constant was introduced between biomass and enzyme concentration.

The theoretical basis of the Michaelis-Menten canonical enzymatic reaction, and fundamentally of the Monod type reactions can be described through a set of ordinary differential equations (ODEs) as discussed in detail by Segel and Slemrod (1989). Considering the reaction presented in Eq. 9 it is possible to describe the rates of change of the individual components through the set of ODEs presented in Table 5. Eq. 26 presents the rate of change of the enzyme (or biomass concentration) and its relation to the substrate, enzyme and complex concentrations, as well as to the reaction rate constants. Eq. 27 presents the rate of change of the substrate concentration and its relation to the enzyme, complex and substrate concentration as well as the complex formation and dissociation constants. Eq. 28 presents the rate of change of the complex concentration and its relation to the enzyme, substrate and complex concentration as well as the complex formation and dissociation

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constants and the product formation constant. Inversely to Eq. 26, Eq. 29 presents the rate of change of product formation and its relation to the complex concentration and the product formation constant. (CHEN; NIEPEL; SORGER, 2010; SCHNELL; MAINI, 2000; SEGEL; SLEMROD, 1989). Assuming initial conditions of $C_E(0) = C_{E0}$; $C_A(0) = C_{A0}$; $C_{EA}(0) = 0$ and $C_P(0) = 0$, Eq. 30 and Eq. 31 describe the mass conservation that allows the simplification of the equations into the coupled ODEs of Eq. 32 and Eq. 33 and the uncoupled ODE of Eq. 34.

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Table 5: ODEs, initial conditions and simplified ODEs describing the rates of change of enzymes, substrate, complex and product for Michaelis-Menten type reactions (SEGEL; SLEMROD, 1989).

Ordinary Differential Equation / Initial Condition / Simplified ODE	Eq. Nr.
$\frac{dC_E(t)}{dt} = -k_1 * C_E(t) * C_A(t) + k_{-1} * C_{EA}(t) + k_2 * C_{EA}(t)$	Eq. 26
$\frac{dC_A(t)}{dt} = -k_1 * C_E(t) * C_A(t) + k_{-1} * C_{EA}(t)$	Eq. 27
$\frac{dC_{EA}(t)}{dt} = k_1 * C_E(t) * C_A(t) - k_{-1} * C_{EA}(t) - k_2 * C_{EA}(t)$	Eq. 28
$\frac{dC_P(t)}{dt} = k_2 * C_{EA}(t)$	Eq. 29
$C_{A0} = C_A(t) + C_{EA}(t) + C_P(t)$	Eq. 30
$C_{E0} = C_E(t) + C_{EA}(t)$	Eq. 31
$\frac{dC_A(t)}{dt} = -k_1 * (C_{E0} - C_{EA}(t)) * C_A(t) + k_{-1} * C_{EA}(t)$	Eq. 32
$\frac{dC_{EA}(t)}{dt} = k_1 * (C_{E0} - C_{EA}(t)) * C_A(t) - k_{-1} * C_{EA}(t) - k_2 * C_{EA}(t)$	Eq. 33
$\frac{dC_P(t)}{dt} = k_2 * C_{EA}(t)$	Eq. 34

Where:

$dC_E(t)/dt$: rate of change of enzyme concentration at time "t"

$dC_A(t)/dt$: rate of change of substrate concentration at time "t"

$dC_{EA}(t)/dt$: rate of change of enzyme-substrat complex concentration at time "t"

$dC_P(t)/dt$: rate of change of product concentration at time "t"

$C_E(t)$: concentration of enzyme at time "t"

$C_A(t)$: concentration of substrate at time "t"

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$C_{EA}(t)$:	concentration of enzyme-substrate complex at time “t”
$C_P(t)$:	concentration of product at time “t”
k_1 :	forward rate constant
k_{-1} :	reverse rate constant
k_2 :	catalytic rate constant
C_{A0} :	Initial (total) substrate concentration
C_{E0} :	Initial enzyme concentration

This set of ODEs does not have a simple solution and is a classic example of a stiff differential equation system. To study this system Segel and Slemrod (1989), applied the singular perturbation theory where after an initial fast transient, one (or more) of the dependent variables were regarded as in steady state with respect to the instantaneous values of the other dependent variables. The argument is that... *“...at high concentrations of substrate in regard to free enzymes ($C_{A0} \gg C_{E0}$) the latter will immediately combine with another molecule of substrate and thus achieve a quasi-steady-state resulting in a complex concentration that is practically constant ($dC(t)/dt \approx 0$)...”* This assumption will be valid if the initial transient state is practically irrelevant, characterizing the standard Quasi-Steady-State-Assumption (sQSSA). They demonstrated that the sQSSA is valid at the general condition shown in Eq. 35, where the sum of the initial substrate concentration in the reactor and the Michaelis-Menten constant is significantly higher than the initial enzyme concentration in the reactor. At $dC_{EA}/dt \approx 0$ it is possible to solve the differential equation system with regard to C_{EA} , dC_{EA}/dt and dC_A/dt as shown in Eq. 36, Eq. 37 and Eq. 38. The Michaelis-Menten

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kinetic is the solution of the slow phase of the dynamic ODE system for the condition presented in Eq. 35. Substituting Eq. 36 into Eq. 34 the product concentration is the uncoupled ODE shown in Eq. 38, which typically stands for the reaction velocity described in Eq. 10. Table 6 summarizes the fundamental condition and simplified sQSSA equations.

Table 6: Conditions and Simplification through the sQSSA

Simplified Equation for the sQSSA	Eq. Nr.
$\frac{C_{E0}}{C_{A0} + K_M} \ll 1$	Eq. 35
$C_{EA}(t) = \frac{C_{E0} * C_A(t)}{C_A(t) + K_M}$	Eq. 36
$\frac{dC_A(t)}{dt} = \frac{-k_2 * C_{E0} * C_A(t)}{C_A(t) + K_M}$	Eq. 37
$\frac{dC_P(t)}{dt} = \frac{k_2 * C_{E0} * C_A(t)}{C_A(t) + K_M}$	Eq. 38

Where:

C_{A0} :	Initial substrate concentration in reactor
C_{E0} :	Initial enzyme concentration in reactor
K_M :	Michaelis-Menten constant
$C_A(t)$:	concentration of substrate at time "t"
$C_{EA}(t)$:	concentration of enzyme-substrate complex at time "t"
$dC_A(t)/dt$:	rate of change of substrate concentration at time "t"
$dC_{EA}(t)/dt$:	rate of change of enzyme-substrat complex concentration at time "t"
$dC_P(t)/dt$:	rate of change of product concentration at time "t"
k_2 :	catalytic rate constant

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Under different initial conditions, e.g. an excess of enzyme concentration, the condition presented in Eq. 35 is not fulfilled. The excess of enzyme condition is known as the “reverse Quasi-Steady-State-Assumption” (rQSSA), under these conditions all substrate would immediately form a complex with the excess enzyme resulting in a quasi-steady-state, in which the substrate concentration is practically constant ($dC_A/dt \approx 0$). The solution for this set of differential equations does not result in the Michaelis-Menten kinetics. (SCHNELL; MAINI, 2000; SEGEL; SLEMMOD, 1989). Thus, Michaelis-Menten type kinetics are a particular solution of a stiff ordinary differential equation system with the boundary condition presented in Eq. 35.

4.2. ANAEROBIC DIGESTION MODELING

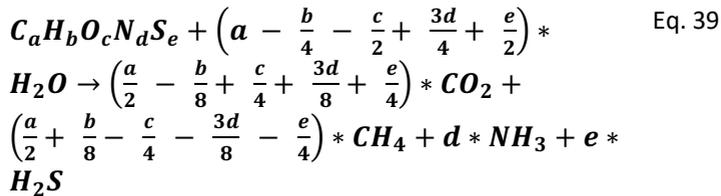
Anaerobic digestion is the decomposition of organic material, in the absence of oxygen, to methane (CH_4) and carbon dioxide (CO_2). The understanding of the anaerobic digestion process has developed from general stoichiometric reactions to the detailed analysis of metabolic pathways and the thermodynamic and kinetic description of possible dynamic pathways. Stoichiometric based approaches have developed to a more dynamic understanding of the individual steps of anaerobic digestion. Currently the ADM1 from the International Water Association (IWA) summarizes the main findings on the anaerobic digestion process. This chapter describes the fundamental stoichiometry, as well as the anaerobic digestion steps

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and the commonly applied kinetic approaches based on the ADM1 Model, on the original publications of its authors, as well as on diverging approaches.

4.2.1. STOICHIOMETRY OF THE BIOGAS PRODUCTION AND BIOGAS POTENTIAL

In the first half of the 20th century, researchers executed studies on how much biogas to expect from the anaerobic digestion of specific substances. Buswell and Neave (1930) already executed an extensive study on biogas production and composition. Buswell and Mueller (1952) presented a stoichiometric estimate of the maximum possible biogas production, which was extended by Boyle in 1976. Today, the extended Buswell and Boyle equation is used to estimate the maximum theoretical biogas production (VDI, 2014) (Eq. 39).



Given that methane and carbon dioxide are respectively at the beginning and end of the oxidation scale of all carbon compounds it is possible to deduce a deproportioning² reaction for most carbon containing molecules. The more reduced the molecule the higher the

² Redox reaction where one element is oxidation and reduction source.

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methane content, the more oxidized the higher the carbon dioxide content. Table 7 presents examples of biogas potential based on the Buswell and Boyle equation.

Table 7: Calculated biogas potential based on the Buswell and Boyle Equation (VDI 2014)

Substance	Name	Chemical Formula	Gas Production [l/kg]	Methane content [%v]
<i>Carbohydrate</i>	Glucose	$C_6H_{12}O_6$	740	50
<i>Protein</i>	Glutamin	$C_5H_{10}N_2O_3$	760*	45*
<i>Long Chain Fatty Acid</i>	Oleic Acid	$C_{18}H_{34}O_2$	1420	71

*Considering all ammonia stays in solution

Detailed understanding of the individual degradation steps allowed a further extension of the stoichiometric approach to include biomass production and intermediate by-products of several substances, resulting in the development of dynamic models.

4.2.2. ANAEROBIC DIGESTION PROCESS AND MODELING APPROACHES

Four main degradation steps describe the anaerobic digestion process, namely hydrolysis, fermentation, anaerobic oxidation and methanogenesis, with intermediate products such as monomers from proteins and carbohydrates, organic acids and inorganic ions resulting in final products CH_4 and CO_2 . Figure 2 presents the basic biochemical processes of the anaerobic digestion.

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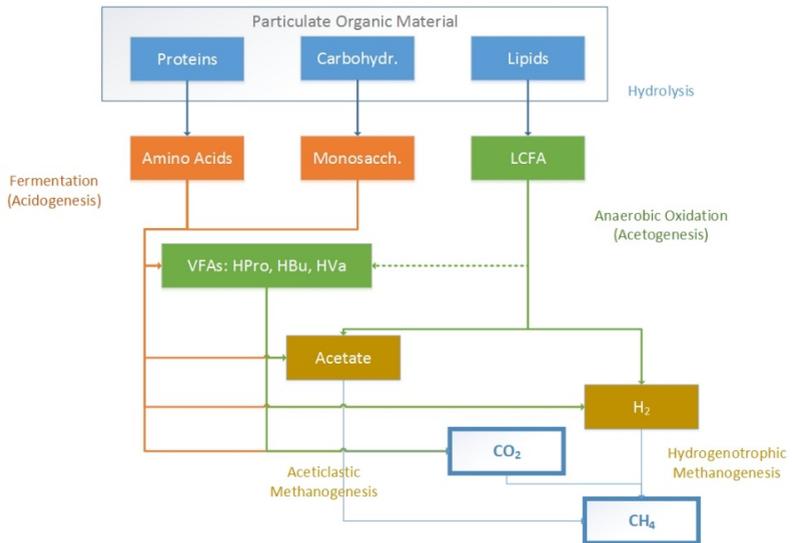


Figure 2: Anaerobic Digestion in four phases (Adapted from Batstone et al, 2002b).
LCFA: Long Chain Fatty Acids; VFA: Volatile Fatty Acids; HPro: Propionic Acid; HBu: Butyric Acid; HVa: Valeric Acid

The input polymeric substrate disintegrates into smaller molecules. Exoenzymes hydrolyze carbohydrates to monosaccharides, proteins to amino acids and lipids to long chain fatty acids (LCFAs); in a second step, fermentative microorganisms process the monomers to volatile fatty acids (VFAs) such as valerate, butyrate, propionate and acetate, as well as hydrogen and carbon dioxide. The organic acids oxidize anaerobically to acetate, hydrogen and carbon dioxide by acetogenic bacteria. Two different processes lead to volatile fatty acid formation, or acidogenesis. On the one hand, monosaccharides and amino acids ferment to volatile fatty acids (VFA), and on the other

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hand anaerobic oxidation transforms long chain fatty acids (LCFA) to VFAs. Finally, during the methanogenic phase, hydrogen, carbon dioxide and acetate metabolize to methane and carbon dioxide through hydrogenotrophic or acetoclastic methanogenesis. The following chapters describe each step and its modeling approach.

HYDROLYSIS

“The complete enzymatic hydrolysis step is a complex multi-step process for carbohydrates, proteins and lipids, which may include multiple enzyme production, diffusion, adsorption, reaction and enzyme deactivation steps”. The term hydrolysis in anaerobic digestion processes is used to describe the decomposition of complex organic material to monomers and can be characterized by one of two conceptual models (BATSTONE et al., 2002a):

- 1) Microorganisms secrete enzymes to the bulk liquid and the enzymes adsorb onto a particle or react with a soluble substrate.
- 2) Microorganisms attach to a particle, produce enzymes near that particle and benefit from the soluble products released by the enzymatic reaction.

The complexity of the process increases when biologic effects are considered. According to Gallert, Winter and Svardal (2015) the necessary exoenzymes for hydrolysis are usually not available or are only available in small concentrations. The authors state that an increased exoenzyme expression only occurs when cells identify

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dissolved metabolites, indicating the presence of the original biopolymers.

Hydrolysis of particulate waste and sludge is often modeled through first order kinetics (PAVLOSTATHIS; GIRALDO-GOMEZ, 1991; SIEGRIST; RENGGLI; GUJER, 1993; SIEGRIST et al., 2002). However, not all particulate material can be degraded with equal facility given that it is affected by a large number of factors, including particle size (EASTMAN; FERGUSON, 1981). The ADM1 separates between the hydrolysis of carbohydrates, proteins and fats, describing each one of these processes with its own first order kinetic constant (BATSTONE et al., 2002a).

Hydrolysis of particulate material can be the slowest step in the anaerobic digestion chain. Gujer and Zehnder (1983) argue that no significant accumulation of soluble organic compounds are found in a mature digester used to stabilize domestic sludge, and typically less than 10% of the total organic carbon in a digestion reactor is soluble. They conclude that the rate of gas production is proportional to the net rate of particle solubilization. Thus, the hydrolysis of the particulate organic substances determines the required detention time of the sewage sludge in the digester. Gossett and Belser (1982) proposed first order kinetics to describe the overall anaerobic digestion of waste activated sludge. Pavlostathis and Gossett (1986) write that the predominant degradable constituent of [waste] activated sludge is particulate protein and describe hydrolysis as the

Theoretical Background

most likely rate-limiting step regarding substrate availability, being significantly slower than cell death or lysis. These observations result in simple models that describe the complete anaerobic digestion process through first order kinetics.

More recently, Vavilin et al. (2007) suggested modeling of hydrolysis from municipal solid waste through Contois kinetics, arguing that models describing particulate hydrolysis coupled to the growth of hydrolytic bacteria provide significantly better results than first order kinetics. Ramirez et al. (2009) also suggest Contois kinetics to model thermophilic anaerobic digestion of pre-treated waste activated sludge. On the other hand, Pavlostathis and Giraldo-Gomez (1991) argue that the Contois model is in essence a variation of the Monod model where the K_s value is a function of the initial substrate concentration and could be described as a Monod model with a variable K_s value, thus questioning the relevance of the Contois model.

Hill (1983) argues that Contois type kinetics, as suggested by Chen and Hashimoto (1980), combine 1st order and Monod type kinetics reaching a very simple approach but losing the ability to predict process failure. He proposes a lumped model to describe the combined process of hydrolysis and acidogenesis. In his publication, Hill proposes Monod kinetics to simulate the anaerobic digestion of animal waste, based on the biodegradable volatile solids concentration. He argues that the only kinetic approach that allows

Theoretical Background

the prediction of process failure in the dynamic phase are Monod kinetics. Hill was able to show that with Monod kinetics it was possible to simulate wash out as well as process inhibition situations.

Vavilin and his colleagues analyzed the degradation of complex organic matter, evaluating four types of hydrolysis kinetics and fitting them to experimental data. The Authors investigated first order, Monod, Contois and a two-phase surface dependent kinetic model. The two-phase model assumed a first phase of bacterial colonization, where bacteria cover the surface of the solids and release hydrolytic enzymes, and a second phase, where a constant depth per unit of time degradation occurs. All four simulated kinetics fitted the experimental data for swine waste, cattle manure and sewage sludge comparatively well. The authors also simulated data on the hydrolysis of cellulose and sewage sludge over a wide range of solids retention times (0-15 days and 0-60 days respectively). The degradation of cellulose fitted first order, Contois and two-phase kinetic models. The first order kinetic model was considered inadequate for not describing the wash out phenomena of the biomass contributing to hydrolysis. The Contois and two-phase kinetics models showed a good fit for the degradation of sewage sludge, however, the authors did not present a discussion on the fit of first order and Monod kinetics.

Sanders et al. (2000) studied the hydrolysis of particulate starch of different particle sizes in batch reactors, modelling hydrolysis by

Theoretical Background

considering the particle surface as the main driver of the reaction rate. This resulted in an equation that includes the substrate density, average particle radius and a surface based hydrolysis constant. Hydrolysis rates of 0.4 ± 0.1 g starch/(m²*h) were identified. Particle diameter ranged between less than 10 µm up to 80 µm. The study showed that the particle size of the substrate had an effect on the hydrolysis rate constant. Considering the variable particle size of waste materials such as sludge the study concluded that the hydrolysis rate constant should be determined experimentally for each sludge.

Miron et al. (2000) investigated the effect of sludge retention time on the hydrolysis of primary sludge at low temperatures (25 °C). The authors analyzed the concentration of long chain fatty acids (LCFA), proteins and carbohydrates. Digestion at sludge retention times (SRT) of 3 to 15 days were investigated. The primary sludge concentration at inflow was 20 g_{TS}/l (TVS 81.1%). The results showed that, at temperatures of 25 °C and solids retention times higher than 10 days, methanogenic conditions prevailed, while for solids retention times below 8 days, acidogenic conditions dominated. Analysis showed, that about 20 % of the sludge is already in a hydrolyzed form, and that hydrolysis is the rate-limiting step for carbohydrates, lipids and all particulate substrates, while hydrolysis and acidogenesis are limiting for the conversion of proteins. None of the hydrolysis rates of the individual components (LCFA, carbohydrates and proteins) followed first order kinetics, under

Theoretical Background

neither acidogenic nor methanogenic conditions. The authors indicate that specific surface area, particle shape and particle size distribution strongly affect hydrolysis and that a surface dependent approach should describe hydrolysis kinetics.

Yasui et al. (2008) also evaluated hydrolysis of primary sludge in batch experiments. They argued that a single composite variable is not appropriate to describe the total sludge degradation reaction, considering the inherently different characteristics of primary and waste activated sludge. Results showed three distinctive primary sludge fractions. One fraction is easily degradable and removed in less than a day. Increase in seed sludge or substrate improved this degradation rate. The authors suggested a Monod or Contois kinetic approach to describe this behavior. A second fraction presented a delayed degradation and the behavior attributed to the particulate fraction of the primary sludge. Here the authors proposed a first order kinetic to model the degradation rate. A third slowly degradable fraction with a biomass independent kinetic reaction was suggested. A particle break up model (PBM) was presented. This model assumed that the specific disintegration rate was constant and that the particles were only available for acidogenesis after the last stage of hydrolysis.

In review, hydrolysis is still considered the least well-defined step of the anaerobic digestion process.

Theoretical Background

FERMENTATION (ACIDOGENESIS)

According to the ADM1, acidogenesis in anaerobic digestion is the fermentation of amino acids and carbohydrate monomers to volatile fatty acids (VFA). Fermentation is defined as a microbial process in which organic material is converted to intermediate degradation products (butyrate, propionate, etc.), to the methane precursors acetate and hydrogen, and to biomass, without an additional electron donor or acceptor. Thus, this mechanism of hydrogen production is not inhibited by higher hydrogen concentrations.

Generally, anaerobic fermentation reactions are not inhibited; however, their metabolism is substrate dependent. When modeling this process, organic substrate availability as well as nitrogen deficiency are included. Modeled by Monod kinetics, acidogenesis is the fastest process in the anaerobic digestion chain. Stoichiometry and reaction constants are broadly described in literature. (ANGELIDAKI, ELLEGAARD, AHRING, 1999; BATSTONE et al. 2002a/b; GUJER; ZEHNDER, 1983; KALYUZHINI, 1997; PAVLOSTATHIS; GIRALDO-GOMEZ, 1991; VAVILIN; LOKISHNA, 1996).

ANAEROBIC OXIDATION (ACETOGENESIS)

Higher organic acids, such as LCFAs and VFAs, degrade to acetate in an anaerobic oxidation step. Monod kinetics describe this process. However, several external factors affect the reaction velocity and influence anaerobic oxidation.

Theoretical Background

Anaerobic oxidation requires an additional external electron acceptor such as the hydrogen ion or carbon dioxide, resulting in hydrogen gas and formate production respectively. Maintaining low partial pressures of these electron carriers is essential to achieve a thermodynamically favorable reaction. (BATSTONE et al., 2002a). The analysis of the chemical reactions and their free Gibbs energy describe the essential condition for an effective anaerobic oxidation.

Table 8 shows the stoichiometric reactions of the acetogenesis of butyrate and propionate standard conditions (25°C and 100 kPa) and pH 7. These reactions are endergonic at standard conditions as shown by their free Gibbs energy at pH 7 (Eq. 40 and Eq. 41). (GALLERT; WINTER; SVARDAL, 2015; THAUER; JUNGEMANN; DECKER, 1977)

Table 8: Acetate production from butyrate and propionate and its standard Gibbs free energy at pH 7, 25 °C and 100 kPa (GALLERT; WINTER; SVARDAL, 2015)

Chemical Reaction	Gibbs Energy	Free	Eq. Nr.
$C_4H_7O_2^- + 2H_2O \rightarrow 2C_2H_3O_2^- + 2H_2 + H^+$	$\Delta G^{0'} = + 48,3$ kJ/Reaction		Eq. 40
$C_3H_5O_2^- + 3H_2O \rightarrow C_2H_3O_2^- + HCO_3^- + 3H_2 + H^+$	$\Delta G^{0'} = + 76,5$ kJ/Reaction		Eq. 41

The dissolved hydrogen (H₂) concentration significantly influences the Gibbs free energy. If there is a hydrogen sink, the reaction can be thermodynamically favorable. This is possible in syntrophy with hydrogenotrophic methanogenesis in a limited range of hydrogen

Theoretical Background

concentrations. The Gibbs free energy for different conditions can be calculated according to Eq. 42 (adapted from THAUER; JUNGEMANN; DECKER, 1977). Figure 3 shows the thermodynamic reaction window where butyrate and propionate degradation is possible at pH 7.0 and 25 °C.

$$\Delta G' = \Delta G^{0'} + RT * \ln \left(\frac{[C]^c * [D]^d}{[A]^a * [B]^b} \right) \quad \text{Eq. 42}$$

Where:

$\Delta G'$: Gibbs free energy

$\Delta G^{0'}$: Gibbs free energy at standard conditions and pH 7 (25°C and 10⁵ Pa)

R: Ideal gas constant

T: Temperature [K]

[A]^a and [B]^b: molar concentrations of the substrates and their stoichiometric coefficients

[C]^c and [D]^d: molar concentrations of the products and their stoichiometric coefficients

Theoretical Background

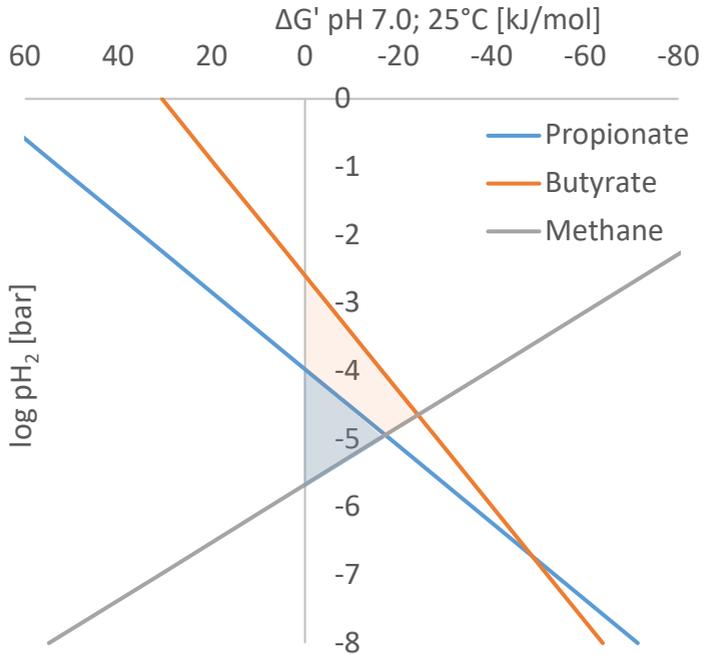


Figure 3: Thermodynamic window of exergonic propionate and butyrate acetogenesis and hydrogenotrophic methanogenesis, 0.001 mol/l for HCO_3^-/CO_2 and methane partial pressure of $0.7 \cdot 10^5$ Pa. (adapted from SAHM, 1981)

Under the conditions presented in Figure 3, propionate degradation is thermodynamically possible at partial pressures of hydrogen (H_2) lower than 10^{-4} bar, while the anaerobic oxidation of butyrate is possible at significantly higher partial pressures of hydrogen of up to 10^{-2} bar. Methane production through the hydrogenotrophic pathway is only thermodynamically favorable at partial pressures of hydrogen higher than 10^{-6} bar. The resulting triangle is the

Theoretical Background

thermodynamic window where degradation of higher volatile fatty acids and production of methane through hydrogenotrophic methanogenesis are thermodynamically favorable.

The same mechanism applies to the LCFA. At low partial pressures of hydrogen (H_2) the monomers from hydrolysis are oxidized mainly to acetate, CO_2 and H_2 , while at higher H_2 partial pressures longer organic acids such as propionate and butyrate are produced, depending on the length and shape of the carbon chain from the LCFA. (GALLERT; WINTER; SVARDAL, 2015)

An accumulation of volatile fatty acids (VFA) might result in acidification and consequent inhibition of the following degradation steps. The microbial groups that degrade fatty acids, acetate and propionate are slow growing bacteria relevant for digester stability. If the production of acetate is greater than its degradation, acetate accumulates and lowers the pH value. Acidogenic and methanogenic bacteria are sensitive to pH variations and an excess of VFA could result in the inhibition of the degradation process. (SIEGRIST; RENGGLI; GUJER, 1993)

METHANOGENESIS

There are two typical pathways to the methane production, namely acetoclastic methanogenesis and hydrogenotrophic methanogenesis. Acetoclastic methanogenesis occurs through the fermentation of acetate, producing methane and carbon dioxide (THAUER; MÖLLER-ZINKHAN; SPORMANN, 1989). Hydrogenotrophic

Theoretical Background

methanogenesis occurs through the reduction of carbon dioxide and oxidation of hydrogen to produce methane. A third pathway to methane production is the oxidation of acetate to carbon dioxide and hydrogen followed by hydrogenotrophic methanogenesis (BATSTONE et al, 2002a). These processes are known respectively as acetoclastic methanogenesis (AM), hydrogenotrophic methanogenesis (HM) and syntrophic acetate oxidation (SAO) (GALLERT; WINTER; SVARDAL, 2015).

Depending on substrate type and substrate concentration, different microorganisms and methanation pathways prevail. I.e., at concentrations of ammonia below 200 mg/l, AM prevailed for a selected set of sludge types fed with sodium acetate, while at higher ammonia concentrations, the methane production pathway shifted to a combination of SAO and HM. (HAO et al., 2016). Irrespective of the methanogenic pathway, Monod kinetics model methanogenesis.

O'Rourke (1968) in Gossett and Belser (1982) suggested that the rate-limiting step in anaerobic digestion of raw wastewater sludge is the fermentation of volatile fatty acids to methane. He implicates, that methane kinetics are the rate limiting digestion step, regardless of the fed substrate. Gossett and Belser (1982) however recommend a separate modeling of primary and waste activated sludge, proposing the O'Rourke Monod kinetic based approach for primary sludge and a first order kinetic approach for waste activated sludge.

4.2.3. DEVELOPMENT AND APPLICATION OF ANAEROBIC DIGESTION MODELS

Simulation of anaerobic digestion processes occurs through the combination of mass balances and reaction kinetics at different levels of complexity. Depending on the presented challenge and available computing capacities, different approaches are sensible. The simulation model depends on the model purpose, from biogas yield to improved reactor design and comprehension of complex interactions of the biologic system.

While complex model structures are ideal for process analysis, much simpler model structures may be required for design and hydraulic analysis. This has emphasized the use of steady state models, and single step, first order kinetics. As operational considerations become more important, structured complex models may also become more relevant. Three different classes of models can be identified: (BATSTONE, 2006).

- 1) Exclusive, very simple models that have a single rate determining step;
- 2) Minimalist, with a minimum number of steps necessary for a specific purpose; and
- 3) Inclusive, where all (known) steps and interactions are included

Theoretical Background

Single rate determining models for wastewater treatment sludge based on first order kinetics allow straightforward digester design and acceptable design precision. In general, the first order kinetic approach is practical at low substrate concentrations. Under these conditions, Monod kinetics approach first order kinetics (Figure 1) (BATSTONE, 2006). The first order kinetic approach however does not explicitly consider the effect of biomass in the anaerobic process.

Graef and Andrews (1974) proposed a dynamic model that included mass balances for the gas phase and liquid phase based on chemical equilibria, as well as a biologic phase based on Monod kinetics. The purpose of the dynamic model was to provide guidelines for improving digester operation by identifying process indicators, assessing the design and operational factors of digester stability and formulate suitable digester control strategies. Their results indicated that improved stability with regard to organic overload could be achieved by increasing the effective residence time, alkalinity, influent substrate concentration and through digested sludge recycling. Noticeably the first three measures could be reached by simple sludge thickening.

Aiming at a kinetic model that accurately described the fermentation of different animal wastes with acceptable simplicity, Hill (1983) proposed a dynamic model based on Monod kinetics. A relevant aspect of this model was to identify system failure due to high concentration of inhibiting substances as well as washout situations.

Theoretical Background

This model considered two distinct types of microbial masses, one for the production of acids and the other for the production of methane. A maximum biodegradability constant based on the type of animal waste and measured as volatile solids was proposed. Simplified input parameters 'lumped' the effects of two or three basic Monod parameters into one parameter that varies with substrate. Conventional Monod kinetics require many inputs regarding chemical and physical characteristics of the waste. By 'lumping' Monod kinetic parameters according to waste type, these inputs may be reduced and simplified to the point where they can be determined for complex substrates without seriously reducing the predictive ability or accuracy of the model. Four basic variables applied, namely: total volatile solids concentration, temperature, hydraulic retention time and waste type. All presented mass balances and differential equations assumed a completely mixed reactor. Compared to measured literature data, these simulations presented errors between 0 % and 25 %.

Angelidaki, Ellegaard and Ahring (1993) proposed a model that included an enzymatic hydrolytic step and four bacterial steps and involving 12 chemical compounds applying first order and Monod kinetics. The focus of the model was to predict ammonia inhibition and included a detailed description of pH and temperature characteristics to simulate free ammonia concentration accurately. Free ammonia and acetate constituted the primary modulating factors. It simulated the digestion of cattle manure in continuous

Theoretical Background

stirred tank reactors, and results compared favorably with experimental data.

The anaerobic digestion system is an extremely complex and variable system, models that try to describe real situations have to consider complex physical, biological and engineering aspects. Relevant parameters can be the mass transport between the interfaces in solid, liquid and gaseous system, buffering conditions from several systems like the carbonate equilibrium and the ammonia equilibrium, the interactions between syntrophic microorganisms and the actual active mixing behavior of the reactor. A compilation of several of the proposed models resulted in the IWA-ADM1. It is a structured model that includes multiple steps describing biochemical and physicochemical processes. This model includes the following biochemical processes:

- disintegration of particulates,
- hydrolysis of the disintegrated particles of carbohydrates, proteins and long chain fatty acids through first order kinetics,
- acidogenesis from sugars and amino acids to volatile fatty acids, such as propionate and butyrate, and hydrogen through Monod kinetics,
- acetogenesis of fatty acids (LCFA and VFA) to acetate; and
- acetoclastic and hydrogenotrophic methanogenesis.

Theoretical Background

- Inhibitions functions due to pH, hydrogen and ammonia concentration are also considered.
- Physicochemical modeling regarding ion association and dissociation, such as the ammonia or carbonate equilibriums.

The ADM1 implementation includes a set of differential and algebraic equations describing a series of sequential and parallel steps. The ADM1 model aims at increasing model application, further development work on process optimization and control, allow direct implementation in full-scale plants, establish a common basis for further model development and validation studies to make outcomes more comparable and compatible and assisting technology transfer from research to industry. (BATSTONE et al. 2002 a/b)

The ADM1 model has found extensive application in literature (e.g. ASTALS et al., 2013; MENDES; ESQUERRE; QUEIROZ, 2015) and expanded through several extensions and variations. Disintegration and hydrolysis steps are still the most unclear kinetic processes and several expansion proposals are suggested, such as the utilization of Contois kinetics to simulate hydrolysis of waste activated sludge (RAMIREZ et al., 2008) and a particle break up model (PBM) to simulate the disintegration/hydrolysis of primary sludge (YASUI et al., 2008). New process inhibitions and favored pathways are constantly being identified, such as that ammonia inhibition on methanogenesis

Theoretical Background

could favor pathway shifts from acetoclastic methanogenesis to syntrophic acetate oxidation coupled with hydrogenotrophic methanogenesis (HAO et al., 2016), and are likely to expand the modelling systems.

Specifically for sewage sludge, Siegrist et al. (2002) presented a model with seven biologic processes including biomass decay. It aims at modeling the combination of physico-chemical and biologic interactions, looking to describe the pH and temperature dependence, as well as ammonia inhibition of acetate and propionate conversion to simulate the effect of protein and nitrogen rich waste. Particle degradation occurs through one single hydrolysis step, while different steps describe the fermentation of amino acids and sugars and the anaerobic oxidation step of LCFA. As in the ADM1, the authors included ammonia, acetate, hydrogen and pH inhibitions effects.

Overall, several dynamic minimalistic or inclusive models were developed through time, resulting in an increasing insight to the anaerobic digestion process. However, their application is only limited.

“In kinetic modelling, an important question to be answered refers to the detail of description to be applied. In principle, organisms are very complex and it is easy to construct a very complicated model. These models are, however, in most cases difficult to handle as they contain a large number of empirical

Theoretical Background

parameters and hence can be verified only with extreme efforts on the part of the investigator. Such models are hardly more easy to handle than reality itself and are of little practical value to reactor design.” (ROELS, 1982)

4.3. SLUDGE PRODUCTION ON WASTEWATER TREATMENT PLANTS

Technical installations for the anaerobic digestion for wastewater treatment exist since the end of the 19th century and have been evolving ever since. The „Emscher Brunnen“ or Imhoff Tank was patented in 1906 to treat wastewater sludge anaerobically (IMHOFF, 1979). In the USA of 1930, anaerobic digestion reduced waste mass and produced a combustible gas of commercial interest on wastewater treatment plants. Buswell and Neave (1930) already knew how fast which type of substrate degraded and how much biogas could be produced. Anaerobic treatment is now widely used for sludge treatment on WWTPs. This chapter briefly describes anaerobic sludge digestion in combination with conventional activated sludge process with nutrient removal on WWTPs and presents typical substrates for digesters produced on WWTPs, namely primary and waste activated sludge.

4.3.1. ACTIVATED SLUDGE PROCESS WITH ANAEROBIC DIGESTION

The activated sludge process is responsible for aerobically decomposing the organic material in wastewater to carbon dioxide,

Theoretical Background

water and nitrogen. Often an anaerobic treatment of the solid phase produced in primary and secondary settling tanks follows the activated sludge process. Figure 4 presents a typical activated sludge process for wastewater treatment with anaerobic sludge stabilization.

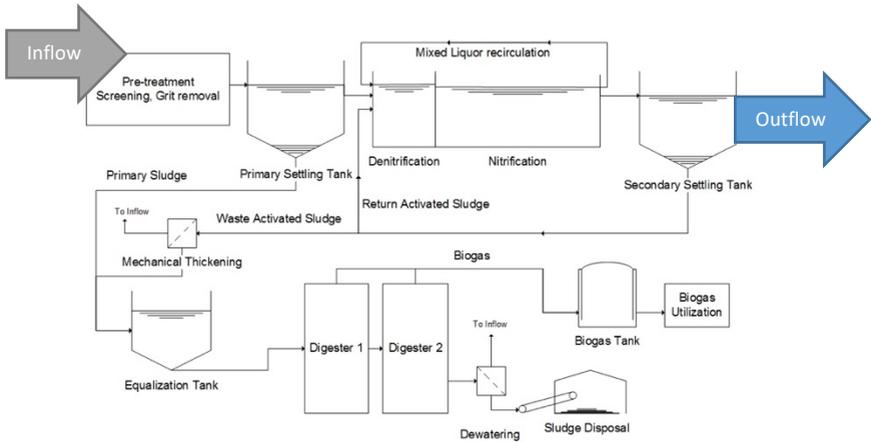


Figure 4: Typical conventional WWTP design

After pre-treatment steps such as screening and grit removal, the wastewater flows through a primary settling tank where particulate material and part of the colloidal organic matter separate from the dissolved organics in the wastewater. From the primary settling tank, the wastewater flows to the activated sludge process where microorganisms oxidize the organic carbon and nitrogen to carbon dioxide, water and nitrate in an aerobic environment. The nitrate rich mixed liquor is recirculated to an anoxic denitrification zone where microorganisms oxidize the inflowing organic carbon to carbon

Theoretical Background

dioxide and water through the utilization of the nitrate bound oxygen, reducing nitrate to nitrogen. The nitrification and denitrification process occurs in separate tanks or, through an intermittent aeration or localized aeration, in a single tank. Figure 4 presents a typical pre-denitrification process, where the nitrate reduction to nitrogen occurs before the nitrification process. The mixed liquor flows into the secondary settling tank where separation of the treated wastewater from the aerobic and anoxic microorganisms takes place. The treated wastewater leaves the WWTP at an outflow. Most microorganisms are recirculated to the aeration tank in the return activated sludge and part of the microorganisms are separated in the waste activated sludge (WAS).

The primary sludge (PS) at the bottom of the primary settling tank is concentrated and collected in a sludge-collecting trough. It is pumped either directly into the anaerobic digester or first stored in a thickening and equalization tank. The PS removal from the sludge-collecting trough occurs once a day or several times a day, depending on WWTP size, operation and automation level. On smaller, non-automated WWTPs, PS removal occurs in the morning after thickening in the sludge collection trough overnight and pumped directly into the anaerobic digester. On larger WWTPs, PS removal occurs several times a day and usually fed to an equalization tank before feeding to the digester.

Theoretical Background

The separated waste activated sludge (WAS) is thickened. On modern WWTPs, mechanical WAS thickening equipment are screens, like belt or disk thickeners; on more traditional WWTPs WAS thickening occurs statically, either through recirculation of the WAS to the primary settling tank or in a separated tank. The thickened sludge is pumped to the anaerobic digester as waste activated sludge.

In Figure 4 the primary and waste activated sludge are pumped from the equalization tank into the anaerobic digester. In the digester, part of the organic material decomposes anaerobically to biogas, resulting in the production of methane and carbon dioxide. This biogas can produce energy such as heat, electricity and fuel, or it can be a material source, e.g. CH_4 and CO_2 for the chemical industry. The residual digestate is composed of water, inorganic material and organic material that is not anaerobically decomposable. The digested sludge is usually mechanically dewatered. After dewatering, the final sludge has to be disposed of. Common disposal options are use as bio solids, incineration and landfilling, depending on the country and legislation. The water of the dewatering process is returned to the beginning of the treatment process.

4.3.2. SUBSTRATES

Anaerobic digesters on WWTPs typically receive two distinct substrates, namely primary sludge (PS) and waste activated sludge (WAS). The WWTP design significantly influences the masses and concentrations of these individual sludge types. Furthermore, co-

Theoretical Background

substrates from other WWTPs, industry, agriculture or the municipal solid waste industry can be added to anaerobic digesters.

Primary sludge originates from primary settling tanks (PSTs). Typically, PSTs are designed based on the surface overflow rate (SOR) derived from the necessary settling velocity (Eq. 43). The median SOR varies between 20 and 60 m³/(m²*d).

$$\text{SOR} = \frac{v_{WW}}{A_{PST}} \quad \text{Eq. 43}$$

Where:

SOR: Surface overflow rate

v_{WW}: Flow Wastewater

A_{PST}: Surface area of the primary settling tank

Alternatively, the average hydraulic retention time (τ_{PST}) is used as a design parameter (Eq. 44). It typically varies between 0.5 h and 2.0 h. Figure 5 presents the effect of the hydraulic retention time on the removal of total solids, suspended solids and chemical and biochemical oxygen demands (COD and BOD respectively) in a primary settling tank according to Sierp in Imhoff (2007).

$$\tau_{PST} = \frac{V_{PST}}{v_{WW}} \quad \text{Eq. 44}$$

Where:

τ_{PST}: Hydraulic retention time in the primary settling tank

v_{WW}: Flow Wastewater

V_{PST}: Volume primary settling tank

Theoretical Background

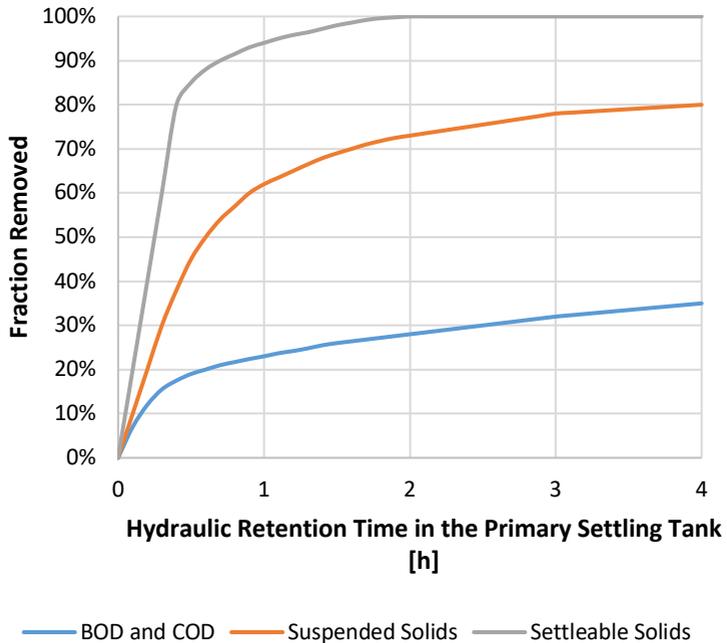


Figure 5: Effect of hydraulic retention time in the primary settling tank on removal of particulate solids, suspended solids and chemical and biochemical oxygen demand according to Sierp in Imhoff (2007)

There is a proportionality between the hydraulic retention time in the primary settling tank and the removal of BOD/COD, total solids and suspended solids. About 85% of settleable solids, 45% of suspended solids and 20% of BOD/COD are removed within 30 min. In 2 hours more than 95% of the settleable solids, about 75% of suspended solids and about 35% of BOD/COD are removed from the wastewater and accumulate in the primary sludge. No significant change in solids

Theoretical Background

and BOD/COD removal occurs after 4 hours of hydraulic retention time in primary settling tanks. The primary sludge thickens within the PST and is pumped to an equalization tank or directly to the digester. Table 9 presents typical total solids and volatile solids concentrations.

If the primary settling tank removes too much carbon, this can result in carbon shortage in the activated sludge process, requiring an extra carbon source. Shorter hydraulic retention times (typically with higher surface overflow rates) in primary settling tanks are preferred to increase the availability of organic carbon to the denitrification process. A longer hydraulic retention time (typically lower surface overflow rate) results in a bigger removal of suspended solids and in an increase of primary sludge for more biogas production in the anaerobic digester. The primary settling tank removes between 10 % and 40 % of the influent COD. The design of the primary settling tank is determining the mass of energy rich primary sludge that goes to the anaerobic digester (SCHMITT et al., 2011).

Waste Activated Sludge is produced in the aeration tank. The mass and quality of the produced WAS will be influenced by the activated sludge age. Higher sludge age will result in a less biodegradable waste activated sludge through the accumulation of inert materials from the inflow and recalcitrant decay products (Gossett and Belser, 1982). Consequently, the biogas production potential of the older waste activated sludge will decrease (BOLZONELLA et al., 2005).

Theoretical Background

Sludge age is the residence time of the aerobic sludge age in a reactor and is determined according to Eq. 45 (ATV-DVWK, 2000).

$$\tau_{AS} = \frac{V_{AT} * C_{TS-AT}}{v_{WAS} * C_{TS-WAS} + v_{WW} * C_{TS-WW}} \quad \text{Eq. 45}$$

Where:

τ_{AS} : Sludge age activated sludge [d]

V_{AT} : Volume aeration tank [m³]

C_{TS-AT} : Concentration of total solids in aeration tank [kg/m³]

v_{WAS} : Flow waste activated sludge [m³/d]

C_{TS-WAS} : Concentration of total solids waste activated sludge [kg/m³]

v_{WW} : Flow wastewater [m³/d]

C_{TS-WW} : Concentration of total suspended solids wastewater [kg/m³]

Design sludge ages for wastewater treatment plants with nitrification and denitrification and an anaerobic digester are around 11 days. WWTPs designed as prolonged aeration usually do not have anaerobic digesters and the sludge stabilization occurs aerobically. Typical design sludge ages for prolonged aeration treatment are 25 days.

The inflow to the WWTP and water temperature influence biomass growth in the activated sludge tank, altering the solids content in the tank, consequently affecting sludge age. The inflow of a WWTP is variable throughout the day and affected by rainfall and snowmelt. A partial equalization occurs in the pipeline system and rain overflow basins. Nevertheless, aerobic bacteria will receive variable daily loads. In cold climate areas, lower temperatures in the winter will result in lower bacterial activity. In this situation WWTPs increase the

Theoretical Background

solids concentration (and consequently sludge age) in the aeration tank to compensate lower biologic activity.

Co-substrates for digesters on WWTPs in Germany are often composed of sludge from other WWTPs, as well as organic wastes from industry, especially the food and feed industry. Smaller WWTPs without sludge stabilization send their thickened sludge to larger WWTPs for processing. This sludge quality can vary widely, from high-energy primary sludge to high sludge age and low energy WAS. Food companies can deliver their high-energy organic wastes to the WWTP, for direct feed to the anaerobic digester. The properties of each sludge are individual.

In Brazil, to avoid the added cost of building sludge treatment on the water treatment plant (WTP), some WWTPs receive this sludge as **co-substrate**. The WTP sludge reaches the WWTPs through the wastewater canalization. The WTP sludge settles in the primary settling tank, channels through the anaerobic digester and is disposed with the WWTP sludge. This process does not reflect negatively on the effluent quality of the WWTP. However, there is an increase in the disposed solids mass. (MARGUTI, 2012)

The design and operation characteristics of the WWTP affect the solids content in the primary and waste activated sludge. Table 9 presents a summary of typical total solids and total volatile solids properties of PS and WAS. Table 10 presents common biogas production potential considering added and removed total volatile

Theoretical Background

solids. The raw sludge fed to anaerobic digesters presents combined properties of PS, WAS and potential co-substrates.

Table 9: Typical solids and volatile solids properties of sludge

Sludge Type	TS [%]	TVS [% _{TS}]	Deg. Fr. [%]	Reference
Primary sludge	2.0 – 8.0	70 % - 90 %	ca. 70 %	DWA, 2014
	1.0 – 6.0	60 % - 85 %	n. a.	METCALF &
	2.0 – 8.0	60 % - 80 %	n. a.	EDDY, 2014 WEF, 2009
Waste activated sludge	0.6 – 0.8	72 % - 76 % ³	ca. 45 %	DWA, 2014
	0.4 – 1.2	69 % - 73 % ⁴ 60 % - 85 %	n. a.	METCALF & EDDY, 2014; WEF, 2009

Table 10: Typical Biogas production potential of wastewater treatment sludge

Sludge Type	Gas Production [l/kg _{TVS_{ad}}]	Gas Production [l/kg _{TVS_{rem}}]	Reference
	U _{GAS_{ad}}	U _{GAS_{rem}}	
Primary sludge	400 – 500		PINNEKAMP et al., 2017
Waste activated sludge	295 – 470		
WAS Prolonged aeration	275 – 460		
Raw sludge		750 – 1120 800 – 1000	METCALF & EDDY, 2014 WEF, 2009

³ Median for BOD/COD elimination, 5 days sludge age.

⁴ Median for N elimination, 10–15 days sludge age.

4.4. ANAEROBIC DIGESTER DESIGN

In the last 40 years, significant use of anaerobic processes has stimulated digester design development. Different process developments for anaerobic wastewater treatment, such as the UASB and EGSB (LETTINGA, 1995), to the increase of biogas use as energy and fuel source, have created a demand for process improvement. Process engineering concepts have been applied more consequently for digester design, such as the introduction of tanks in series for improved sludge decomposition (HEINDL; ROEDIGER, 2016; KEMPTER; SCHMID-STAIGER; TRÖSCH, 2000). Technological advances have allowed (better) mechanical thickening of raw sludge, resulting in the possibility of significantly higher sludge concentrations at digester inflow and better process performance (ENGEL, 2003).

This chapter describes the reactor types and reactor mixing for conventional anaerobic digesters (Ch. 4.4.1) and presents the current background on high load anaerobic digesters (Ch. 4.4.2). Furthermore, it presents the current design recommendations for anaerobic digesters (Ch. 4.4.3), the typical performance equations (Ch. 4.4.4) and the effect of increased loads on digester performance (Ch. 4.4.5).

Theoretical Background

4.4.1. CONVENTIONAL ANAEROBIC DIGESTER REACTOR TYPES AND REACTOR MIXING

The design of anaerobic digesters consolidated over several decades. In general, good digesters require heating to optimal temperature, proper mixing and a uniformly fed energy rich feed. A digester is expected to reduce 80 % to 90 % of the degradable solids fraction in Germany (DWA, 2014) or 38 % of total added volatile solids to attend to the specifications of “Class B” biosolids requirements (EPA, 1994). Digesters are differentiated by reactor shape and mixing technology.

REACTOR TYPES

Typical anaerobic digester designs in Germany are egg shaped and cylindrical with conical top and bottom. In the United States of America (USA), tall and flat cylindrical digesters with flat top and bottom are also common. Anaerobic digesters in South America commonly base on design recommendations from Europe or the USA. Figure 6 presents the typical anaerobic digester designs.

Theoretical Background

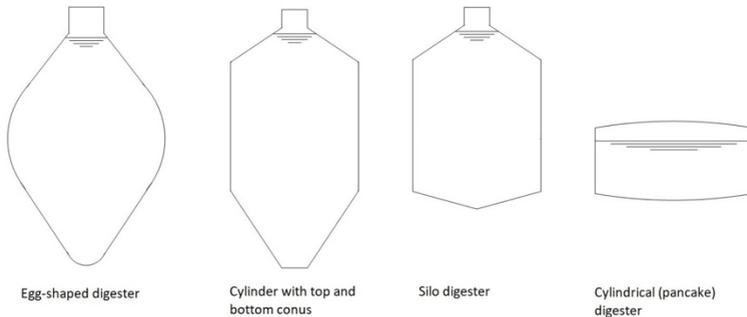


Figure 6: Typical anaerobic digester shapes egg shaped reactor; cylinder with top and bottom conus; Silo digester and shallow vertical cylinder (Adapted from DWA, 2014)

Egg shaped digesters are designed to improve mixing and reduce the demand for cleaning. The tapered base combined with central mixing fosters the resuspension of sediment back into the bulk. This decreases the accumulation of material in the digester and avoids dead-zones. The narrow gas dome design aims at high liquid agitation and thus suppression of foam formation. Instead, the foam remains in the bulk. (WEF, 2009) The egg shaped digester also has static advantages over other designs, it is possible to build larger digesters based on the egg shape design. The largest egg-shaped digesters reach up to 17,000 m³ (DWA, 2014).

Cylindrical digesters with top and bottom conus are common in continental Europe and consist of a cylindrical middle ($H/D \approx 1$) and conical top and bottom. The lower conus has an angle between 45° and 60° to reduce particle accumulation at the bottom, while the upper conus has an angle between 20° and 45°. The largest cylinder

Theoretical Background

with top and bottom conus digesters reach about 5,000 m³. (DWA, 2014). This reactor shape presents similar advantages to the egg-shaped reactor.

The silo, or tall cylinder, digester is a compromise between the cylindrical top and bottom conus and the shallow cylindrical digester. The increased height to diameter ratio allows a few gains in the mixing performance, without the cost (WEF, 2009).

The shallow cylindrical digester has a small bottom slope of a minimum of one vertical to six horizontal. The design allows a variety of mixing systems and application of conventional construction techniques, even for large digester volumes. However, the reactor shape might result in inefficient mixing and dead zones. (METCALF & EDDY, 2014)

REACTOR MIXING

Proper mixing is one of the most important considerations to reach ideal process performance. It is essential to guarantee an effective distribution of the substrate, avoid concentration and temperature gradients, avoid dead zones, reduce short-circuiting, prevent sludge blankets and improve gas removal from the system. Common mixing technologies are recirculation mixing, internal or external draft tube mixers, mechanical stirring and gas injection.

Anaerobic digesters operate continuously for several decades, thus a relevant parameter for the selection of digester mixing is its energy

Theoretical Background

efficiency. Mixing energy, or dissipated power, as a function of reactor volume lies between three and ten Watts per cubic meter of reactor volume, depending on the selected system and rheology of the sludge. Internal draft tubes are reported to demand the lowest specific energy density, between 3 W/m^3 and 6 W/m^3 (DWA, 2014).

Next to the average mixing energy in the digestion system, the local mixing energy is relevant to the stability of the biologic process. The biomass-substrate exchange needs to be effective; however, excess local shear forces can result in the destruction of essential biomass clusters. Furthermore, effective mixing also allows a better control of foam formation. (DICHTL; SCHMELZ, 2015). Figure 7 presents the basic mixing principles of anaerobic digesters, namely: 1) the external pump recirculation, 2) simple biogas injection, 3) internal draft tube with gas recirculation, 4) internal draft tube with mechanical stirrer, 5) a simple mechanical stirrer and 6) external draft tubes with pump recirculation (adapted from METCALF & EDDY, 2014). System variations such as the external draft tube and other gas injection techniques base on the same principles.

Theoretical Background

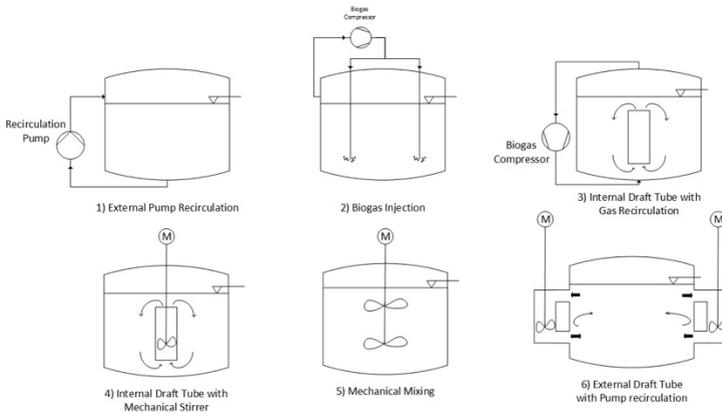


Figure 7: Basic mixing systems of anaerobic digesters: 1) external pump recirculation; 2) Biogas injection; 3) Internal draft tube with gas recirculation; 4) Internal draft tube with mechanical stirrer; 5) Mechanical stirrer and 6) External draft tube with pump recirculation. (Adapted from METCALF & EDDY, 2014)

Recirculation mixing is usually only recommended for digesters smaller than 500 m³, when these are equipped with steep lower conus to avoid formation of dead zones. For a good mixing, the entire volume of the reactor volume should recirculate at least 10 times a day. (DWA, 2014). This type of mixing is more effective when the pumping cycle takes sludge from the bottom and discharges it near or above the gas-liquid interface to break up scum. (METCALF & EDDY, 2004).

Biogas injection, or unconfined gas mixing, capture the biogas in the headspace of the digester, compress it and reintroduce it at the bottom. Bottom diffusers or top mounted lances reintroduce the biogas to the reactor. In these cases, the liquid level in the reactor

Theoretical Background

does not affect mixing performance significantly. The introduction of gas bubbles also allows different flow patterns in the reactor. However, gas mixing can be relatively ineffective, especially for the digester content located below the injection nozzles. (METCALF & EDDY, 2014)

An alternative to the simple introduction of biogas in the digester is to discharge the biogas through confined tubes or introduced a mechanical stirrer within the draft tube creating a gaslift effect. Internal and external draft tubes usually present a good top to bottom mixing and can operate in both directions. Maintenance of external draft tubes is easier. The selection of this mixing technology however limits the liquid level in the reactor. Internal draft tubes are often the technology of choice for the cylindrical and egg shaped reactors. (METCALF & EDDY, 2004). Long draft tubes present the limitation, that it is not possible to reduce the liquid level in the reactor without compromising mixing. The fallout of the mixing can quickly result in foaming and potentially leaking of the reactor content. Thus, operators have equipped the mixing systems with movement monitoring and level sensors to identify foam building. (SCHÄFER; BIENIEK; SCHREIBER, 2016).

Meroney (2009) executed a detailed study on the mixing of mechanical draft tubes. Computational Fluid Dynamics (CFD) simulated the mixing of cylindrical anaerobic digesters of diameters varying between 13 m and 33 m, equipped with single or multiple

Theoretical Background

draft-impeller-tube-mixers. The author noted that tank mixing might deviate from ideal behavior for a variety of reasons associated with placement of inlets, outlets, stratification, and tank geometry. The presence of even a slight density difference between the mixing fluids strongly influenced the progression of mixing. Power to volume ratios between 4.1 W/m^3 and 6.9 W/m^3 were registered.

Mechanical stirring aims to move the complete reactor volume and create a flow pattern. Flow velocities should be higher than 0.3 m/s at the reactor bottom to avoid grit sedimentation. Small fast rotating stirrers are easy to maintain, however excessive local turbulence can disturb particle cohesion and reduce energy efficiency. Slower, larger stirrers connected to a central axle allow better control of the flow pattern. However, paddles, axles and ropes can be focal points of blockages. (DWA, 2014).

4.4.2. HIGH LOAD ANAEROBIC DIGESTER REACTOR TYPES AND REACTOR MIXING

New tools and challenges continuously push the development of digester technology. In particular, mechanical instead of static dewatering of raw sludge now allow thicker sludge flows to the digester (ENGEL, 2003). Fraunhofer IGB in collaboration with Schwarting Biosystems (Formerly Schwarting-Uhde) developed a reactor for anaerobic digestion appropriate to process thick sludge masses, under high sludge loads in short hydraulic retention times, the “High Load Anaerobic Digester” or “HLD”. Initially confined to a

Theoretical Background

specific reactor shape, the design of the HLD developed to a process principle also applied to other reactor types. The high load digestion process requires a reactor type that presents effective mixing and biogas removal.

The high load digester differentiates itself from traditional digesters through its smaller volume and optimized mixing system. This allows the use of different materials such as stainless steel for the construction of the digester. The reactor typically has a cylinder shape, with a small conus at the bottom for grit removal. The improved mixing system combined with the continuous grit removal avoid dead zones and reduction of active digester volume. Currently, two known reactor types operate under high load conditions, the Schwarting-Uhde reactor and the loop reactor.

SCHWARTING-UHDE PROCESS

The Schwarting-Uhde process is equipped with a set of holed platforms within the digester. An impulse pump and an internal vessel for mixing (Figure 8). Hydraulic retention times of 5 to 6 days showed effective digestion performance. The main reported advantages of this process are: 1) the significantly smaller reactor volume, reached through the high organic loading rate and short hydraulic retention times, 2) no significant foaming, and 3) improved sludge degradation, resulting in better dewaterability. (KAMPNER, 2007)

Theoretical Background

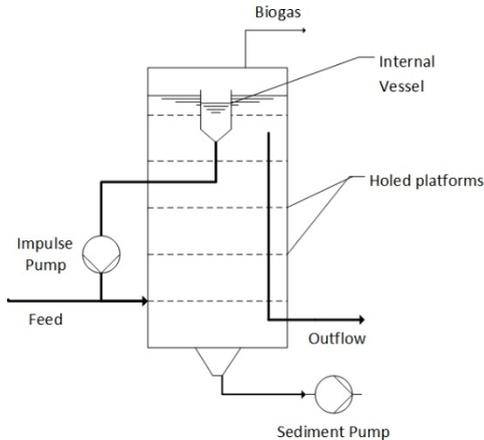


Figure 8: High load anaerobic digester according to the "Schwarting-Uhde" process adapted from Kampner (2007)

Figure 9 presents the mixing system of the *Schwarting-Uhde* reactor. The reactor is equipped with a small internal vessel located at the top third of the reactor, connected to the rest of the reactor through a pipeline equipped with an impulse pump. Through the activation of the impulse pump, the small tank empties into the reactor. The sludge level in the reactor increases. Once the impulse pump turns off, based on the principle of communicating vessels, the sludge level in the reactor equalizes. During the equalization time sludge flows through a set of holed platforms. The velocity of the flow through the holes is higher than in the rest of the reactor allowing local turbulence and partial mixture, which allows the necessary biomass-substrate exchange. The impulse pump activates 3 to 5 times an hour.

Theoretical Background

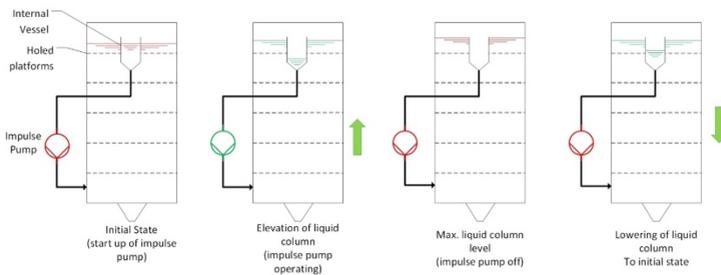


Figure 9: Mixing system of the High Load Digester according to the Schwarting-Uhde process adapted from Kampner (2007)

LOOP REACTOR

A variation of the “Schwarting-Uhde” high load anaerobic digester is the loop reactor reported by Sternad et al. (2016). The installation of two high load loop digesters tackled the sludge digestion of a wastewater treatment plant with seasonal load variation due to industrial wastewater from wine production. During off-season, the reactors operate in series for maximum turnover, while during harvest and production season they operate in parallel to treat the large sludge quantities. The system design allows hydraulic retention times in each reactor as low as 6 d. The reactors are built as loop reactors with gas injection based on the gas lift principle, instead of the holed platforms and impulse pump, from the Schwarting-Uhde process. This reduces the amount of internals in the reactor.

The mixing of the loop reactor used by Sternad et al. (2016) bases on the gas lift effect. The reactor design was based on the model for gas-liquid systems of “mammoth loop reactors” described in Sternad and

Theoretical Background

Blenke (1989), where the mixture of the liquid phase occurs smoothly over the complete reactor volume. Figure 10 shows the mixing principle of the “mammoth loop reactor”.

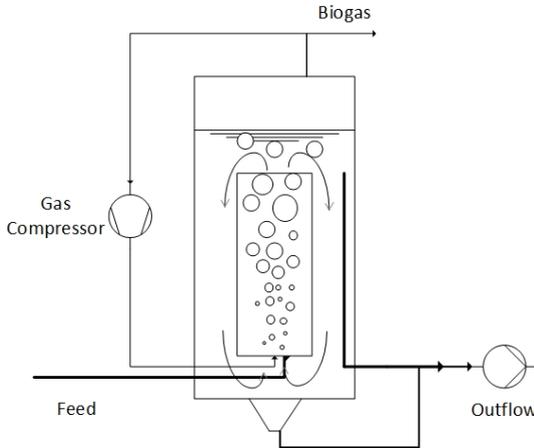


Figure 10: Mixing principle of the mammoth loop reactor (Adapted from Sternad and Blenke 1989)

Similar to the draft tube mixing, the produced biogas is reinjected to the digester at the bottom. However, the internal draft tube in the mammoth loop reactor has different geometry compared to the draft tubes typically installed in the shallow vertical cylinders. This reactor is commonly taller and thinner and aims at moving the complete volume in the reactor through the draft tube using the propulsion from the density difference inside and outside the draft tube provoked by the insufflation of the biogas at the bottom. (STERNAD; BLENKE, 1989)

Theoretical Background

4.4.3. DIGESTER DESIGN PARAMETERS

CSTRs are the typical reactor for anaerobic digesters on WWTPs. Usually digester design bases on defining a digester shape, mixing system and appropriate hydraulic retention time (Table 11). A relevant focus is set on the civil and mechanical engineering challenges that arise from the digester construction. Although anaerobic digestion presents complex degradation kinetics of organic material, the actual digester design rests on simple, single-rate models. The specialized access, as well as the high variation of parameter constants does not facilitate the use of complex models for design. The simplest approach for anaerobic digester process design on wastewater treatment plants, and the one most applied in practical terms, is the determination of the necessary SRT and adequate OLR.

Most reactor designs assume continuous stirred tank reactors (CSTR), with identical sludge retention time and hydraulic retention time, constant density and practically steady state conditions. Typically, there is no sludge recirculation in anaerobic sludge digesters. The minimum HRT limitation in a CSTR is the slowest cell growth. Below that time, cells washout and the biological reaction does no longer take place. In general, there are no defined limits of maximum HRT for anaerobic digesters.

A significant influence on the OLR is the available sludge thickening technology. While higher organic loads are preferred, it is generally

Theoretical Background

harder to reach them. In most cases, the maximum organic loading rate is not reached and HRT is used as a design parameter. The digester volume is determined by dividing the HRT by the expected flow into the digester, as shown in Eq. 46.

$$V = \frac{\tau}{v} \quad \text{Eq. 46}$$

Where:

- V: Reactor volume
- τ : Hydraulic retention time
- v: Inflow to the digester

Peak hydraulic loading determines the maximum inflow to the digester. This can be estimated by combining poor thickener performance with maximum continuous plant loading expected during seven continuous days during the design period (EPA, 1979; METCALF & EDDY, 2004). The DWA M368, 2014, recommends that, when possible, good information on the sludge composition such as total solids and volatile solids concentrations should be determined. Existing wastewater treatment plants should determine the inflow to the digester based on the maximum value of the two-week floating average of produced and thickened sludge volume. The OLR is calculated according to Eq. 47.

$$OLR = \frac{C_{TVS}}{\tau} \quad \text{Eq. 47}$$

Where:

- OLR: Organic Loading Rate
- C_{TVS} : Concentration of total volatile solids
- τ : Hydraulic retention time

Theoretical Background

Low volatile solids concentrations can result in negative impacts on the digester. If substrate concentration is too low, the increased flow will reduce HRT and TVS destruction. Consequently, TVS is removed in the digestate instead of being transformed to biogas, methane generation reduces, alkalinity reduces, heating requirements increase, there is a higher demand in dewatering capacity and sludge disposal costs increase. Excessive organic loading rates can result in digester failure due to formation inhibiting substances. (METCALF & EDDY, 2004, p. 1513). Table 11 presents recommended hydraulic retention times and organic loading rates for digester design from literature.

In Table 11, it is possible to observe that some authors define different HRTs and OLRs according to WWTP size, measured in people equivalents. Recommendations for smaller WWTPs are higher HRTs and lower OLRs, while on larger WWTPs lower HRTs are acceptable. A lower HRT and higher OLR will result in smaller digesters overall reducing investment and operational costs. Overall OLRs between $1 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ and $5 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ are recommended while the hydraulic retention time varies between 15 d and 20 d. The high load digester design differentiates itself by presenting a five-day hydraulic retention time and significantly higher OLRs, reached through thickening of the raw sludge.

Theoretical Background

Table 11: Suggested anaerobic digester design parameters for CSTR mesophilic digesters

Reference Parameter	HRT (τ) [d]	OLR [kg TVS/(m³*d)]	Source
Connected Population WWTPs < 50.000 PE	20	2.0	(DICHTL; SCHMELZ, 2015)
Connected Population WWTPs 50.000 – 100.000 PE	15 – 20	2.0 – 3.5	
Connected Population WWTPs > 100.000 PE	15	3.5 – 5.0	
Connected Population WWTPs < 50.000 PE	20 – 28 (14 – 19) *	1.0 – 1.4 (2.9 – 3.9) *	(DWA, 2014)
Connected Population WWTPs 50.000 – 100.000 PE	18 – 25 (13 – 17) *	1.1 – 1.5 (3.2 – 4.2) *	
Connected Population WWTPs > 100.000 PE	16 – 22 (12 – 15) *	1.2 – 1.7 (3.6 – 4.5) *	
Mesophilic low rate CSTR (no mixing, no heating)	30 - 60	0.04 – 0.10	(WEF, 2009)
Mesophilic high rate CSTR (mixing and heating)	15 – 20	1.6 – 4.8	(EPA, 1979; METCALF & EDDY, 2014; WEF, 2009)
High load digester for mesophilic CSTR	5 – 7	8 – 10	(MERZ et al., 1999)

*Design parameters for the first digester of two digesters in series

Theoretical Background

4.4.4. DIGESTER PERFORMANCE EQUATIONS

An assumption, based on experience or experiments, often determines the organic solids removal performance of a reactor. More recently, kinetic models were included. The current edition on sludge stabilization from the German Association for Water, Wastewater and Waste – DWA (2014) recommends that 85% of the easily digestible volatile solids added to the digester be removed during the digestion process. In order to determine the necessary HRT it is assumed that hydrolysis is the limiting kinetic step and first order kinetics are assumed to define the overall process. Eq. 48, Eq. 49 and Eq. 50 from Table 12 present the fundamentals of this design approach. The hydrolysis constant is temperature dependent according to Eq. 48. Eq. 49 and Eq. 50 characterize the total outflow concentration of substrate and the volatile solids stabilization fraction.

METCALF & EDDY (2014) suggest *“the design of anaerobic sludge digestion should be based on an understanding of the fundamental principles of biochemistry and microbiology”*. Nevertheless, they present a few traditional empirical approaches to the anaerobic digester design for discussion. Table 12 presents these design equations. For the solids retention time method, at a known inflow to the digester, a COD decomposition is measured (or assumed) for a specific hydraulic retention time, based on empirical data. Eq. 51 calculates the biomass production rate. First order kinetics describe endogenous activity of biomass. The volatile solids stabilization

Theoretical Background

fraction is determined according to Eq. 52 and is a function of the daily organic solids inflow, the daily organic solids removed during digestion and the produced biomass. Eq. 53 estimates the methane production, where the degraded COD that does not become biomass partially converts to methane under standard temperature and pressure (STP) conditions.

Chen and Hashimoto (1980) argue that the effluent quality of biological treatment systems for organic wastes has to be dependent on the influent organic waste concentration. For a treatment system operating at a constant temperature and retention time, the concentration increase of the inflow should have an effect on the effluent substrate concentration and the volumetric substrate reduction rate. Monod kinetics do not explicitly present this property and thus they selected Contois kinetics for their system. The effluent quality of the biologic treatment is a function of influent substrate concentration based on Contois kinetics. Through solving the substrate mass balance with Contois kinetics, Eq. 54 describes the substrate concentration at the outflow of the digester including a refractory factor for the non-biodegradable portion of the organic solid material.

Theoretical Background

Table 12: Design equations for CSTR anaerobic digesters in steady state presented in literature

Source	Description	Equation	
DWA (2014)	Hydrolysis constant	$k_{Hyd} = 0.045 * 1.072^{(T-10^{\circ}C)}$	Eq. 48
	Biodegradable TVS concentration	$C_{bTVS} = \frac{C_{bTVS0}}{1 + k_{Hyd} * \tau}$	Eq. 49
	Biodegradable TVS stabilization fraction	$U_{bTVS} = \frac{k_{Hyd} * \tau}{1 + k_{Hyd} * \tau}$	Eq. 50
METCALF & EDDY, 2014	Biomass production rate in TVS	$r_c = \frac{Y_{C/A} * (C_{bCOD0} - C_{bCOD}) * v}{1 + k_{end} * \tau}$	Eq. 51
	Biodegradable COD stabilization fraction	$U_{bTVS} = \frac{(C_{bCOD0} - C_{bCOD}) - 1.42 * C_{cTVS}}{C_{bCOD0}}$	Eq. 52
	Methane production (STP)	$v_{CH_4} = 0.35 * [(C_{bCOD0} - C_{bCOD}) * v - 1.42 * C_{cTVS} * v]$	Eq. 53
Chen and Hashimoto (1980)	Total substrate concentration at digester outflow	$C_{TVS} = C_{TVS0} * \left[\frac{C_{RTVS}}{C_{TVS0}} + \frac{(1 - \frac{C_{RTVS}}{C_{TVS0}}) * Y_{C/A} * B}{k_{Cmax} * \tau - 1 + Y_{C/A} * B} \right]$	Eq. 54

Theoretical Background

Where:

k_{Hyd} : Hydrolysis constant [1/d]

T: Temperature [°C]

C_{bTVS} : Biodegradable total volatile solids concentration [g_{TVS}/l]

C_{bTVS0} : Inflow biodegradable total volatile solids concentration [g_{TVS}/l]

τ : Average hydraulic and sludge retention time [d]

U_{bTVS} : biodegradable volatile solids or COD stabilization fraction [1]

r_C : Biomass production rate [$g_{TVS}/(l*d)$]

$Y_{C/A}$: Yield of biomass from substrate [$g_{VSSproduced}/g_{CODremoved}$]

C_{bCOD} : Biodegradable COD concentration [g_{COD}/l]

C_{bCOD0} : Inflow biodegradable COD concentration [g_{COD}/l]

v: Flow to and from digester [l/d]

k_{end} : Endogenous respiration rate [1/d]

1.42: conversion factor for biomass TVS to COD [g_{COD}/g_{TVS}]

V_{CH_4} : Methane Volume produced per day [Nm^3/d]

0.35: conversion factor methane produced per biodegradable COD removed at STP [$m^3_{CH_4}/kg_{COD}$]

C_{TVS} : Total volatile solids concentration [g_{TVS}/l]

C_{TVS0} : Inflow total volatile solids concentration [g_{TVS}/l]

CC_{TVS} : Cells as total volatile solids concentration [g_{TVS}/l]

C_{RTVS} : Recalcitrant total volatile solids concentration [g_{TVS}/l]

B: Contois growth parameter constant

k_{Cmax} : specific growth rate of microorganisms

Theoretical Background

4.4.5. EFFECT OF INCREASED OLR AND DECREASED HRT ON ANAEROBIC DIGESTION

Kapp (1984) investigated the effect of substrate concentration and organic loading rate on anaerobic digestion. He showed that the thickening of the raw sludge up to 9 % TS can have a significant effect on the reactor volume. Overall, the thickening of the sludge will reduce the volume of the total inflow to the digester, which results in smaller digester volumes for the same HRT.

Kapp (1984) also evaluated the effect of solids concentration on reactor performance. The author did not observe any significant differences in solids removal at increased solids concentration at the inflow ranging from 0.9 % to 9 % total solids fraction. Kempter, Schmid-Staiger and Trösch evaluated the anaerobic digestion of sludge of 11 different wastewater treatment plants in a two stage digester pilot plant, operated with a total hydraulic retention time of 11 days (5.5 days per reactor). In their experiment, contrary to the results from Kapp, 1984, an increase of solids concentration at the inflow showed positive influence on the TVS removal and biogas production. The authors found that high removal fractions and high biogas production were only achieved at organic loading rates above $2.5 \text{ kg}/(\text{m}^3 \cdot \text{d})$.

The WWTP in Berlin Waßmannsdorf treats the wastewater of about one third of Berlin. They executed full-scale experiments to evaluate the effect of higher loads and shorter hydraulic retention times in

Theoretical Background

their digesters. The WWTP is equipped with six anaerobic digesters of 8,000 m³ each. Between the years 2000 and 2002, they changed their digester operation from five digesters in parallel, to two digesters in parallel followed by one digester in series. An organic load increase from 1.39 kg TVS/(m³*d) to 2.73 kg TVS/(m³*d) took place, associated with an increase in biogas production from 36,000 m³/d to 47,000 m³/d and reduction in total volatile solids at the outflow of the digester from 70 Mg/d to 61 Mg/d. (ENGEL, 2003). In this case, a higher loading rate and decreased hydraulic retention time increased the total biogas production by about 20 %. The serial digester operation was not maintained given the operational challenges associated with higher specific biogas production.

Aiming at increasing the biogas production on the WWTP in Köhlbrandhöft, Hamburg, the local utility company decided to execute a test run, changing operations from part of their digesters from parallel to serial operation. The WWTP is equipped with eight main mesophilic primary digesters and two secondary digesters. Plant digesters ran at hydraulic retention times as low as 6 days. Operational conditions did not allow reducing HRT further, given that the biogas production in the first digester was significant, resulting in decreased sludge density, due to higher biogas content in the overall sludge. The installation was not prepared to handle the increase in reactor specific biogas production, resulting in interruption of the experiment. Stable volatile fatty acids measurement showed no biologic overloading. (SCHÄFER; BIENIEK; SCHREIBER, 2015). Thus, as

Theoretical Background

for Berlin Waßmanskorf, technical and not biologic boundaries limited the operation of the digesters under increased organic loading rate and reduced hydraulic retention time.

5. MATERIALS AND METHODS

This chapter presents the data collection and preparation methods necessary to analyze anaerobic digester performance. The information processed and presented in this thesis divides two basic groups: operational information and design information. Operational information originates from operational data books kept by the WWTP operators, where trained WWTP operators executed all presented laboratory analysis and registered the online measurements. Design data originates from interviews with WWTP operators and design documents.

The characteristics of the input substrates, sludge management strategies and anaerobic digester design influence digester performance. Input substrates are essentially primary sludge, waste activated sludge and co-substrates. The WWTP design, such as tank sizes, or pumping and piping capacities, as well as the wastewater treatment strategies, such as activated sludge recirculation and storm water management influence the substrate quality. Thus, to evaluate substrate quality, it is necessary to understand the substrate origin. Chapter 5.1 presents a brief characterization of each evaluated WWTP and its design characteristics. Chapter 5.2 describes the type of data available from the operational data books, as well as its measuring methods. Chapter 5.3 presents the methods used for data processing regarding WWTP characterization, sludge treatment characterization and anaerobic digester performance.

Chapter 5.4 describes the data preparation, such as elimination of outliers and implausible data, data clustering and error propagation.

5.1. WASTEWATER TREATMENT PLANT

DESCRIPTION

This chapter presents the twelve analyzed WWTPs. Eleven WWTPs are located in Germany and one is located in Brazil. Through visits to each WWTP, analysis of design plans and extensive interviews with operators, the fundamental information to each WWTP was established. Their common feature is the conventional activated sludge process with anaerobic sludge stabilization. Three variations of the activated sludge process occur on these WWTPs:

- 1) Pre-denitrification: the denitrification tank is set before the nitrification tank, spatially separating the anoxic zone (denitrification), where heterotrophic biomass reduces nitrate to nitrogen and the aeration zone (nitrification), where biomass transforms organic nitrogen and ammonia to nitrate and oxidizes BOD/COD to carbon dioxide (CO₂) and water. This process requires about 11 days of aerobic sludge age and is typical on German WWTPs.
- 2) Intermittent denitrification: the activated sludge tanks have two different operational settings one aerated (nitrification) and one anoxic (denitrification), thus there is no spatial separation between processes. Automation often occurs

Materials and Methods

through dissolved nitrate concentration measurement in the reactor. This process also requires about 11 days active sludge age and is typical on German WWTPs.

- 3) Carbon removal: the reaction occurs in one tank with one operational setting, namely aeration. The aim of the process is to reduce the BOD/COD concentration of the wastewater and presents no specific aim on nitrogen removal. This process requires about five days of sludge age and is still typical in Brazil⁵.

Each analyzed WWTP presents anaerobic digesters for sludge stabilization. However, the digesters present different setups:

- a) Conventional digester: typically designed for 20 days hydraulic retention time, organic loading rate of up to 4 $\text{kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ and 35 °C operational temperature.
- b) Conventional digester + Secondary digester: After the primary digester, some WWTPs are equipped with a secondary digester. However, secondary digesters are

⁵ Nitrogen removal on WWTPs is not mandatory in Brazil. WWTP effluent needs to present a maximum of 60 mg $\text{BOD}_{5,20}/\text{l}$ or 80 % BOD removal in the State of Sao Paulo (SÃO PAULO, 1976). Federal law states maximum of 100 mg $\text{BOD}_{5,20}/\text{l}$ or 60 % BOD removal (BRAZIL, 2005). River water classification determines the required nitrogen concentration. A maximum of 12.5 mg/l nitrogen are allowed in rivers.

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usually not heated. They function as an equalization tank before sludge dewatering.

- c) Conventional digester 25 °C: the anaerobic digester in Brazil was designed for 20 days HRT with no reactor heating, resulting in an average operational temperature of 25 °C. No information on the planned organic loading rate was identified.
- d) High load digester: designed for hydraulic retention times between 5 and 10 days, OLR up to $8 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ and 35 °C to 40 °C operational temperature.
- e) High load digesters in series: After the primary high load digester, some WWTPs are equipped with a second high load digester. Different from the secondary digester of the conventional type, this digester is heated and mixed. Thus, in this case two identical digesters operate in series.

Focusing on anaerobic digester performance, the WWTPs clustering occurred based on anaerobic digestion process and hydraulic retention time. Table 13 presents the four analyzed WWTPs equipped with High Load Digesters (HLDs), its main characteristics and data availability. Table 13 presents the analyzed WWTP equipped with a conventional digester operated at 25 °C (CD 25 °C). Table 14 presents the analyzed WWTPs equipped with conventional digesters operated at 35 °C (CD).

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Table 13: Overview of the analyzed WWTPs equipped with High Load Digesters

Id.	Design PE	Treatment process	Notes	Data availability
HLD 1	60,000	<i>Digester Type:</i> 2 HLD in series <i>Mixing:</i> Schwarting impulse pump <i>WWT:</i> Intermittent Deni. <i>Sludge:</i> PS and WAS mechanical thickening belt filter	PS and WAS jointly thickened through belt filter.	8 years daily avg.
HLD 2	360,000	<i>Digester Type:</i> 2 HLD in parallel followed by 3 conventional digesters <i>Mixing:</i> Schwarting impulse pump <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS and WAS mechanical thickening centrifuges	Runs at fixed 6 days HRT, any excess sludge bypasses to the conventional digesters.	1 year daily avg.
HLD 3	46,700	<i>Digester Type:</i> 2 HLD in series <i>Mixing:</i> Schwarting impulse pump <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS static thickener; mechanical WAS thickening	Design HRT: 5 days	6 years daily avg.
HLD 4	30,000 – 120,000	<i>Digester Type:</i> 2 HLD flexible operation series/parallel <i>Mixing:</i> Loop reactor <i>WWT:</i> Intermittent Deni. <i>Sludge:</i> PS static thickener; mechanical WAS thickening	Digester operation parallel or in series according to sludge load. WWTP was adapted from prolonged aeration to digestion.	1 year daily avg.

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Table 14: Overview of the analyzed WWTP equipped with a Conventional Digester operated at 25 °C

Id.	Design PE	Treatment process	Notes	Data availability
CD 25 °C	315,000	<i>Digester Type:</i> 2 + 1 Cylindrical with conical top and bottom <i>Mixing:</i> External pumping cycle <i>WWT:</i> Carbon removal <i>Sludge:</i> PS directly to digester 3 x day; static WAS thickening	WWTP receives sludge from WTP rich in Fe. PS volume and mass is affected by WTP sludge.	5 years daily avg.

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Table 15: Overview of the analyzed WWTPs equipped with Conventional Digesters

Id.	Design PE	Treatment process	Notes	Data availability
CD 1	55,000	<i>Digester Type:</i> 2 Cylindrical with conical top and bottom <i>Mixing:</i> External pumping cycle + biogas injection <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS and WAS static thickening in PST	Digesters designed to run in parallel; now in series. Sludge level reduced to allow operation in series	6 years daily avg.
CD 2	600,000	<i>Digester Type:</i> 2 parallel primary + 1 secondary, Egg shaped <i>Mixing:</i> Draft tube with mechanical stirrer <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS static thickener; mechanical WAS thickening	Event regulated PS removal from PST. High precision sludge management. Continuous digester feeding.	3 years monthly avg.
CD 3	160,000	<i>Digester Type:</i> 1 Cylindrical with top and bottom conus <i>Mixing:</i> External pumping cycle + biogas injection <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS static thickener; mechanical WAS thickening		2 years daily avg.
CD 4	345,000	<i>Digester Type:</i> 2 parallel egg shaped <i>Mixing:</i> Draft tube with mechanical stirrer <i>WWT:</i> Pre-Denitrification <i>Sludge:</i> PS static thickener; mechanical WAS thickening		1 year daily avg.

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Id.	Design PE	Treatment process	Notes	Data availability
CD 5	16,000	<p><i>Digester Type:</i> 1 Cylindrical with top and bottom conus</p> <p><i>Mixing:</i> External pumping cycle</p> <p><i>WWT:</i> Intermittent Deni.</p> <p><i>Sludge:</i> PS directly to digester 1 x day; mechanical WAS thickening</p>	Feed to WWTP through gravity. Hydraulic flow control to PST.	3 years daily avg.
CD 6	50,000	<p><i>Digester Type:</i> 1 Cylindrical with top and bottom conus</p> <p><i>Mixing:</i> External pumping cycle</p> <p><i>WWT:</i> Intermittent Deni.</p> <p><i>Sludge:</i> PS directly to digester 1 x day; mechanical WAS thickening</p>	Recent expansion of WWT with limited sludge recirculation due to reduced pipe diameter of old process.	3 years daily avg.
CD 7	67,000	<p><i>Digester Type:</i> 1 Egg shaped</p> <p><i>Mixing:</i> Draft tube with mechanical stirrer</p> <p><i>WWT:</i> Pre-Denitrification</p> <p>Oversized PST</p> <p><i>Sludge:</i> PS and WAS combined static sludge thickening in extra tank</p>	Originally designed for 120,000 PE, downsized to 67,000 due to load decrease.	3 years monthly avg.

5.2. OPERATIONAL DATA

Essential factors in design and operation of biological treatment systems are the effluent quality, treatment efficiency, and substrate reduction rate (CHEN; HASHIMOTO, 1980). Important requirements are that the parameters involved can be measured and that they represent a key step in the process (BATSTONE, 2006). This chapter presents the relevant information extracted from the operational data books and describes the applied measuring methods.

Operational data books present information on the quantities (flows or masses of water, solids, gas and energy) and the quality (concentrations of solids, pollutants, gas components, etc.) of mass streams flowing through the WWTP, registering online, as well as offline measurements daily. Annex 13.1 shows an excerpt of an operation data book as example, presenting original as well as calculated values. Trained WWTP operators executed all analysis presented in the operational data books and registered all online measurements. Visits and intensive exchange with the operators allowed improved data interpretation.

5.2.1. FLOW MEASUREMENT

Data book analysis resulted in the registration of three relevant flow types:

1. Liquid flows to, from and inside the WWTP, relevant to determine parameters such as hydraulic retention time or sludge age;

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2. Biogas flows out of the digester, relevant to evaluate digester performance; and
3. Electric energy production from the biogas produced in the digester, relevant as a counterpoint to the biogas flow, essential to double-check data quality.

LIQUID FLOW MEASUREMENT

Connected population, industry, infiltration water, rainfall and snowmelt influence the daily inflow and outflow of the WWTP. It usually presents a baseline and peaks that show rain and snowmelt (Annex 13.2). All WWTPs are equipped with flowmeters at the inflow and outflow of the WWTP, and register its values. Table 16 presents the relevant liquid flow information available in an operational data book, the measurement method and its precision.

Table 16: Liquid flow data available in an operational data book

Parameter	Symbol	Unit	Method	Precision
Daily Inflow and outflow	v_{in} and v_{out}	[m ³ /d]	Electromagnetic flowmeter	1 % of rate ⁶
Flow of primary sludge to digester	v_{PS}	[m ³ /d]	Venturi flume meter	(ABB, 2011) 3 % of rate
Flow of WAS to digester	v_{WAS}	[m ³ /d]		(ABNT, 1995)
Flow of sludge to digester	v_s	[m ³ /d]		

⁶ Precision of this measurement can reduce significantly at flow velocities below 0.5 m/s. Gas inclusions can cause significant errors.

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Specific information on primary sludge flows is not available on all WWTPs. On WWTP “CD 1” WAS and PS are thickened jointly in the PST, thus, it is impossible to measure the PS flow. WWTPs “CD 6” and “HLD 3” discharge the primary sludge manually once a day and are not equipped with flow measurements for this stream. All WWTPs are equipped with flow measurements for the WAS stream. Either the thickened, the non-thickened or both sludge volumes are measured (Annex 13.3). Primary and Waste Activated Sludge present different properties. Thus, when available, combined with quality parameters such as total solids (TS), total volatile solids (TVS) or COD, the different sludge streams allow a more precise prediction of sludge degradation and biogas production potential.

All WWTPs present information of the sludge flow fed to the digesters. This information is fundamental to determine the hydraulic retention time in the digester. WWTP CD 4 combines the PS and WAS flows to determine the total flow to the digester, while the other WWTPs are equipped with measuring devices for the raw sludge to the digester. When data is available, the combination of PS and WAS flows is compared to the total sludge for consistency check. Combined with quality parameters, the flow to the digester determines the basic input data for the digester mass balances.

All German WWTPs are equipped with electromagnetic flowmeters for liquid flow measurement. A magnetic field is set up

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perpendicularly to the motion of an electrical conductor by a conductive liquid like water or sludge in a non-conductive pipe. The resulting induced electrical voltage will be proportional to the magnetic field strength and the velocity of the movement according to Faraday's law, thus allowing a flow measurement. A minimum conductivity between 0.05 and 20 $\mu\text{S}/\text{cm}$ is required depending on the device type. The WWTP in Brazil has Venturi flume flow measurement installed. It works based on the principle that the pressure drop for incompressible fluids in a defined geometry is proportional to the flow.

GAS FLOW MEASUREMENT

Biogas production is one of the relevant data sets to determine digester performance and a counterpart to evaluate solids removal. Flow measurements are present for all individual digesters with the exception of the digesters of WWTP HLD 1 and HLD 3. There, only the combined biogas flow of both digesters is measured. The investigated WWTPs presented three different types of flow meters, namely ultrasonic flowmeter, thermal mass flowmeter and lobed impeller totalizer. Table 17 presents the relevant gas flow information available in an operational data book, the measurement method and its precision.

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Table 17: Gas flow data available in the operational data books

Parameter	Symbol	Unit	Method	Precision
Biogas prod.	v_{GasP}	[m ³ /d]	Ultrasonic transit time	1.5 % of rate (ENDRESS & HAUSER, 2016) ⁷
Biogas cons.	v_{GasC}	[m ³ /d]	Lobed impeller totalizer	< 1 % of rate (ABB, 2011) ⁸

The WWTPs in Germany presented ultrasonic flowmeters. Ultrasonic measurement bases on the principle that the propagation velocity of a sound wave in a medium is a material property that changes with the density of the measuring medium. Thus, when a soundwave is emitted diagonally to the flow and the same signal is emitted backwards, the medium density is cancelled and only the medium velocity will be registered. (ENDRESS & HAUSER, 2016).

The WWTP in Brazil presented a lobed impeller totalizer. The totalizer has a rigid measuring compartment between the walls of a stationary chamber and two Figure eight impellers. The impellers rotate due to

⁷ However, sound beam must traverse a representative cross section, therefore flow profile dependent. Requires long inlet and outlet sections. Errors due to deposits might occur. (ABB, 2011)

⁸ Lobed impeller meters are very susceptible to contamination, since it affects the pressure drop. Monitoring and cleaning is required. (ABB, 2011)

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differential pressure. The impellers transfer the gas from the inlet to the outlet. A counter registers the displacement volume cumulatively.

These measurement principles do not inherently include the effect of temperature, or the saturation of biogas with water vapor. Thus, it is possible that a systematic error is present at the biogas production measurement. The correction of the biogas production to STP conditions (273.15 K and 1.01325 bar) is done in two steps: The water vapor partial pressure of the saturated biogas is calculated according to the Magnus Equation (Eq. 55) (VDI, 2014). The gas volume in STP conditions is determined based on the ideal gas law (Eq. 56).

$$p_w = 6.11213 * e^{\frac{17.5043 * T_i}{241.2 + T_i}} \quad \text{Eq. 55}$$

$$V_{STP} = \frac{V_i * (p_i - p_w)}{(T_i + T_{STP})} * \frac{T_{STP}}{p_{STP}} \quad \text{Eq. 56}$$

Where:

- V_{STP} : volume at STP [m³]
- p_w : partial pressure of water vapor [mbar]
- T_i : temperature at operational condition [°C]
- V_i : volume at operational condition [m³]
- p_i : gas pressure at operational condition [mbar]
- T_{STP} : temperature at STP (273.15 K)
- p_{STP} : pressure at STP (1013.25 mbar)

The worst case scenario will occur when an average anaerobic digester has a biogas measurement unit installed close to the digester outflow, the measured biogas is still wet and at digester

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temperature. Assuming digester temperature of 35 °C and 10 mbar overpressure on a low-pressure day ($p_{\text{atm}} = 920$ mbar), the ratio V_{STP}/V_i would be 0.8. When available and viable, a comparison of electricity and biogas production data is executed, to determine if an overestimation bias is present.

ELECTRIC ENERGY

Electric energy production can be a good secondary measurement for biogas production. If all biogas produces electricity, the electric efficiency of the combined heat and power plant (CHP) is known and the biogas composition is available, the energy content of the biogas and consequently its actual volume under STP conditions can be estimated. Table 18 presents the measurement type, its precision and the mathematical procedure to determine biogas volume under STP conditions. This information corroborates the measured biogas values.

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Table 18: Energy flow data available in the operational data books and biogas production estimation

Parameter	Symbol	Unit	Method/Value	Precision/Ref.
Electric energy production	e_{el}	[kWh _{el} /d]	Four wire three phase	2.0 % (EU, 2014) ⁹
Lower Heating Value CH ₄	LHV _{CH4}	[kWh/m ³]	9.97	(ARMSTRONG; JOBE, 1982)
Electric Efficiency CHP	η_{el}	[% _{el}]	Variable depending on size and manufacturer	
CH ₄ Fraction in biogas	CH ₄	[% _v]	Ex.: Infrared beam sensor	2 0.5 % (AWITE, 2016)

5.2.2. QUALITY MEASUREMENT

The execution of mass balances for the anaerobic digesters requires mainly the knowledge of sludge quality. However, part of the sludge quality is influenced by operational parameters on the WWTP, specifically regarding the waste activated sludge. Even though parameters that describe wastewater characteristics (COD, nitrogen series, and phosphorus) were analyzed, they were not explicitly utilized in the WWTP analysis. Biogas quality measurements were

⁹ For Class B precision class and temperatures between 5 °C and 30 °C.

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available on only two of the WWTPs. They were also analyzed, but not explicitly used. Thus, only sludge production relevant data are presented.

Data registration of solids parameters occurs daily or once or twice a week, depending on the size of the WWTP. Table 19 presents the solids composition quality parameters available in the operational data books and the methods used for their determination. The measurement methods for all WWTP except WWTP CD 25 °C are executed according to the Norms of the German Institute for Standardization (DIN). WWTP CD 25 °C follows the standards presented by the “*Associação Brasileira de Normas Técnicas - Brazilian Association of Technical Norms*” (ABNT). The followed measurement standards however are directly comparable.

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Table 19: Solids quality parameters from operational data books

Parameter	Symbol	Unit	Precision	Method
Mixed Liquor Suspended Solids	C _{MLSS}	[g/l]	1 g/l	DIN 38409 Part 10 (2007)
Mixed Liquor Volatile Suspended Solids	MLVSS	[% _{MLSS}]	0,1 %	DIN 38409 Part 1 (2001)
Total Solids from Primary Sludge	TS _{PS}	[% _M]	0,1 %	
Total Solids from WAS	TS _{WAS}	[% _M]		
Total Solids from Raw Sludge	TS _{RS}	[% _M]		
Total Solids of Digested Sludge	TS _{DS}	[% _M]		
Total Volatile Solids of Primary Sludge	TVS _{PS}	[% _{TS}]	0,1 %	DIN 38409 Part 1 (2001)
Total Volatile Solids of WAS	TVS _{WAS}	[% _{TS}]		
Total Volatile Solids of Raw Sludge	TVS _{RS}	[% _{TS}]		
Total Volatile Solids of Digested Sludge	TVS _{DS}	[% _{TS}]		

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The detailed knowledge of each solids stream allows a deeper insight into the overall mass balance of the WWTP. The mixed liquor concentrations are relevant for the determination of waste activated sludge (WAS) quality, specifically sludge age. A relevant parameter to establish potential biogas production from WAS.

A specific challenge is the proper sampling of primary sludge. It is very difficult to remove sludge from the primary settling tank in a homogeneous manner, which makes it challenging to properly characterize the primary sludge load (DWA, 2014). Common procedures to remove sludge from the primary settling tank base on volumetric or visual procedures. Either, a specific volume of sludge is removed daily, e.g. through a time controlled pump or valve, or the sludge is removed as long as it seems thick. Some WWTPs monitor the sludge removal in the primary settling tank through a sludge-blanket level measurement. However, the initial flow to sludge equalization or the digester will generally have a higher solids concentration than the final flow.

It is common practice on WWTPs to collect a single random sample of primary sludge at a random time during the sludge removal of the primary settling tank to characterize the sludge. It is very likely that the single random sample does not characterize the complete primary sludge. Thus, primary sludge loads are often subject to significant systematic error. To compensate this variation, some WWTP operators randomize the sampling time, to reach a more

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accurate yearly average. However, there still is significant variation in solids concentration of primary sludge.

One of the most relevant information obtained in the operational data books is the TS and TVS concentration to and from the digester. This allows the fundamental evaluation of digestion efficiency and can be juxtaposed to the biogas production. Analysis of TS and TVS data from WAS is executed when available. Data on primary sludge characteristics may have to be inferred based on the difference between total sludge and WAS.

5.3. DATA PROCESSING

After evaluating the operational data books, determining plausibility and removing improbable outliers, the operational parameters of the wastewater treatment plant were determined, the sludge characteristics were established and the digester performance characterized.

5.3.1. SLUDGE PRODUCTION ON THE WWTP

Two main parameters influence substrate, or raw sludge quality: reactor volumes and sludge management. The following sludge production parameters were determined: Hydraulic retention time in the primary settling tank (PST), PST surface overflow rate (SOR) and activated sludge age. The inflow to the WWTP and the volume from the PST determine the hydraulic retention time in the primary settling tank (Eq. 44). WWTP inflow and PST surface will determine

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the PST surface overflow rate (Eq. 43). Sludge age in the aeration tank is established based on the volumes of the nitrification and denitrification tanks and the total solids content in the nitrification and denitrification tank (C_{TS-AT}) as well as the removed fraction of waste activated sludge (C_{TS-WAS}) (Eq. 45).

In combination with the quality parameters, chemical oxygen demand (COD), total nitrogen and total phosphorus, as well as the flow to or from the WWTP establish the loads to the WWTP and the actual connected population. An estimate of sludge production based on the connected population, COD removal in the PST and COD removal in the activated sludge process allow a comparison between the expected sludge production and the actual sludge production. This is used as data quality check.

5.3.2. SLUDGE TREATMENT ON THE WWTP

Operational parameters of sludge digestion were established based on the daily volumetric sludge flows and concentration of the raw sludge stream. The hydraulic retention time of sludge in the anaerobic digesters was determined based on inflow to the digester and the active digester volume (Eq. 57). Organic loading rates were described as a function of the volatile solids concentration at inflow and sludge volume to the digester and active digester volume, or hydraulic retention time (Eq. 47). In case only the volatile solids fraction was available, a density of $1,020 \text{ kg/m}^3$ was assumed for the raw sludge to determine the solids concentration.

$$\text{HRT Digester [d]} \qquad \tau_D = \frac{V_D}{v_{RS}} \qquad \text{Eq. 57}$$

Where:

- τ_D : HRT Digester
- V_D : Reactor Volume Digester
- v_{RS} : Volumetric flow raw sludge

Periods of acceptably constant HRT in the digester were identified graphically. Some WWTPs had more than one stable operational regime resulting in more than one statistical significant HRT for the same digester. Analysis of variance (ANOVA) confirmed the statistically significant difference. The one-way ANOVA technique (NIST/SEMATECH, 2003) was used to test if the mean among two or more groups of data of hydraulic retention time are equal, assuming the sampled populations are normally distributed. The assumed null hypothesis was that there is no difference in the population means of different samples of the hydraulic retention time. The alternative hypothesis being that the means are not the same. The applied α value was 0.05. The analysis of variance was performed for the hydraulic retention times of WWTPs HLD 1, HLD 3, CD 4 and CD 7. It was executed through the Excel Data Analysis tool “Anova: Single Factor Variance Analysis”.

5.3.3. ANAEROBIC DIGESTER PERFORMANCE

EQUATIONS

The combination of several parameters is necessary to evaluate the performance of anaerobic digesters. Operational routine parameters used to evaluate sludge stabilization quality are TVS at the outflow,

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TVS removal and specific biogas production. (Rosenwinkel, Kroiss, Dichtl, Seyfried and Weiland 2015). Reactor efficiency is determined through the total volatile solids removal in the digester (Eq. 58) as well as through the biogas related parameter, specific biogas production per TVS added (Eq. 59). Furthermore, digester performance determination occurs through reaction rates for TS and TVS removal (Eq. 60 and Eq. 61) and specific biogas production (Eq. 62 and Eq. 63). COD measurements have been shown to be consistent for digester design (KUNST; HELMER; KNOOP, 2013), however none of the evaluated wastewater treatment plants had available data on COD of the sludge phase.

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Table 20 presents the parameters and equations used to determine reaction rates and reaction efficiencies from the operational data books.

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Table 20: Anaerobic digester performance equations assuming CSTR

Parameter	Unit	Equation	
TVS stabilization fraction ¹⁰	[% _m]	$U_{TVS} = \frac{TSO * TVSO - TS * TVS}{TSO * TVSO}$	Eq. 58
Gas per TVS added	[l/kg _{TVSAd}]	$U_G = \frac{v_G}{v_{RS} * TS * \rho_{RS}} * 1000 \frac{l}{m^3}$	Eq. 59
Total solids removal rate	[kg/(m ³ *d)]	$r_{TS} = \frac{(TSO - TS) * \rho_{RS}}{\tau_D}$	Eq. 60
Total volatile solids removal rate	[kg/(m ³ *d)]	$r_{TVS} = \frac{(TSO * TVSO - TS * TVS) * \rho_{RS}}{\tau_D}$	Eq. 61
Biogas production rate	[m ³ /(m ³ *d)]	$r_G = \frac{v_G}{\tau_D}$	Eq. 62
Biogas production rate (from electric energy)	[m ³ /(m ³ *d)]	$r_{Gel} = \frac{P_{el}}{\eta_{el} * 9,97 \frac{P_{tot}}{CH_4} * CH_4 * V_D}$	Eq. 63

¹⁰ Assumption: density is constant for the inflowing and outflowing sludge.

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Where:

- U_{TVS} : Fractional conversion of total volatile solids
- TSO : Total solids fraction at the inflow
- $TVSO$: Total volatile solids fraction as % of TSO
- TS : Total solids fraction in the reactor and at the outflow
- TVS : Total volatile solids in the reactor and at the outflow as % of TS
- U_G : Fractional production of biogas
- v_G : volumetric flow biogas
- v_{RS} : volumetric flow raw sludge
- ρ_{RS} : density raw sludge
- r_{TS} : reaction rate total solids
- τ_D : HRT Digester
- r_G : biogas production rate
- r_{GeI} : biogas production rate from electric energy
- η_{el} : Electric efficiency of the co-generation unit
- P_{el} : Power (electric)
- P_{tot} : Power (total in gas)
- CH_4 : Volumetric fraction of methane in biogas

5.4. DATA PREPARATION

The raw information from the operational data books was prepared to deliver useful information for anaerobic digester analysis. Outliers and implausible data were removed. Relevant data was clustered by average, standard deviation, median, 25 percentile, 75 percentile and 85 percentile as well as maximum and minimum values. The intrinsic uncertainty was determined considering the measurement error and its propagation.

5.4.1. OUTLIERS AND IMPLAUSIBLE DATA

Outliers can significantly affect the evaluation of operational data and influence the statistical parameter values. The following procedure was applied to outlier management: every information available in the operational data books was plotted over time and evaluated regarding consistency. Online data sets were inspected on plausibility and signal drift¹¹. Manually introduced data, such as laboratory measurements, were inspected on plausibility and typos. Aiming to identify errors and inaccuracies, all the data from laboratory analysis was subjected to an outlier identification process. Outliers were defined as “all the values outside three standard deviations (Eq. 65) of a log normal distribution (Eq. 64)”, as shown in Table 21 (LIMPERT; STAHEL; ABBT, 2001). Log-normal distribution was applied, due to the fact that several of the distributions were

¹¹ An implausible online data set is, e.g., negative volume flows, an online data set with signal drift is, e.g. an increasing pH value over time with sudden correction after calibration of the sensor.

skewed. This is typical for distributions with low mean values, large variances and values that cannot be negative, for example mass flows and concentrations (LIMPERT; STAHEL; ABBT, 2001). Improbable outliers were removed. Annex 13.4 shows an example of the distribution analysis of the inflow solids concentration through histograms and determination of outliers for log-normal distribution (Eq. 66).

Table 21: Determination of outliers based on lognormal average and standard deviation values (LIMPERT; STAHEL; ABBT, 2001)

Parameter	Definition	Eq. Nr.
Mean (log Normal distribution)	$\bar{x}^* = \exp\left(\frac{1}{n} * \sum_{i=1}^n \log x_i\right)$	Eq. 64
Standard Deviation (log Normal distribution)	$s^* = \exp\left(\sqrt{\frac{1}{n-1} * \sum_{i=1}^n \left(\log \frac{x_i}{\bar{x}^*}\right)^2}\right)$	Eq. 65
Outlier	$> \bar{x}^* * (s^*)^3 \text{ or } < \bar{x}^*/(s^*)^3$	Eq. 66

Where:

- x_i : independent variable
- \bar{x}^* : mean of log normal distribution
- s^* : standard deviation of log normal distribution
- n : number of (independent) variables in sample

After elimination of improbable outliers, possible systematic errors were investigated. When available, different measurements of the same data were compared. The more plausible data set was selected. If a whole data set is not consistent with literature and no sensible explanation is available to why this data set is so different the data set was marked as unreliable and not used in the present study.

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The volumetric inflow to the digester can be variable, thus a floating average of the inflow was calculated. The floating average time span was determined through the average hydraulic retention time of the digester. If the digester has an average HRT of 20 days, the used floating average was over 20 days, if the digester has an average HRT of 8 days the floating average was over 8 days. If there are only separated primary and waste activated sludge streams recorded, the floating average of each sludge stream was determined and added to determine the total inflow to the digester.

5.4.2. DATA CLUSTERING

Box-plots cluster the data sets obtained from the operational data books. The upper and lower box lines in the box-plot represent the 75 percentile and the 25 percentile respectively, the middle line represents the median. Whiskers represent the minimum and maximum values. The square inside the box-plot represents the average value for secondary reference. Figure 11 presents the accumulated frequency of a value, as well as its intrinsic measurement error. Figure 12 presents the graphical description of the box plot.

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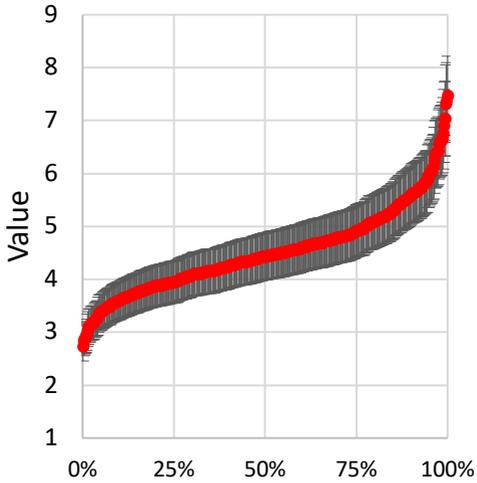


Figure 11: Accumulated frequency of value and intrinsic measurement uncertainty

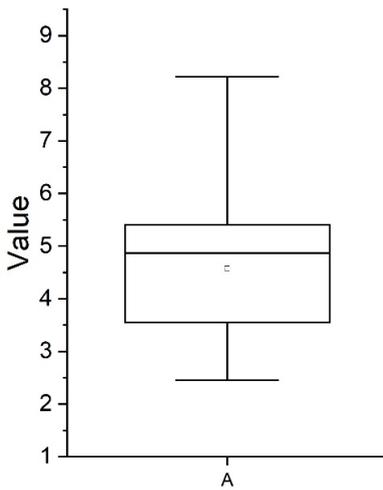


Figure 12: Clustered data in box-plot

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All the box plots present a combination of the data distribution and the intrinsic measurement error. E.g., in Figure 11, the 75 percentile value is 4.9, the intrinsic measurement error is 0.6, thus, in the box plot of Figure 12, the 75 percentile value is 5.5. The 75 percentile and the maximum value include an addition of the intrinsic measurement uncertainty. The 25 percentile in minimum value include a subtraction of the intrinsic measurement uncertainty. For composite data, e.g. specific loading rates (concentration*inflow/reactor volume), mathematical operations (addition, subtraction, multiplication, division) are executed directly from the existing data set. E.g., on April 21st solids concentration was “TS” and sludge inflow was “Q”, thus, solids load was “TS*Q”. The box plots show the distribution of the composite data including error the propagation.

5.4.3. ERROR PROPAGATION

The Tables in chapter 5.2 present the intrinsic uncertainty from the relevant measurements. The composite parameters determined in

Table 20, namely biogas production per added total volatile solids, the total volatile solids removal fraction, the reactor specific biogas production rate and the reactor specific solids removal rate are determined through a combination of measured values and consequently combined uncertainties. Through application of mathematical operations, the intrinsic uncertainty propagates according to the equations presented in Table 22. The uncertainty

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propagation analysis did not include the uncertainty of reactor volumes of the WWTP.

Table 22: Fundamental equations to determine the uncertainty propagation

Mathematical operation	Equation	Eq. Nr.
Sums and subtractions	$(\sigma_x)^2 = (\sigma_u)^2 + (\sigma_v)^2 + \dots (\sigma_n)^2$	Eq. 67
Multiplications and divisions	$\left(\frac{\sigma_x}{x}\right)^2 = \left(\frac{\sigma_u}{u}\right)^2 + \left(\frac{\sigma_v}{v}\right)^2 + \dots \left(\frac{\sigma_n}{n}\right)^2$	Eq. 68

Where:

x: calculated value

u, v, n: measured values

σ : intrinsic uncertainty

6. WWTP AND DIGESTER ANALYSIS

An analysis of 42 years of operational data resulted in the identification of 18 different operational conditions on twelve WWTPs, eight WWTPs with standard anaerobic digesters and four WWTPs equipped with high load anaerobic digesters. High load digesters are identified by the acronym “HLD”, while conventional digesters are identified by the acronym “CD”. Numbers 1 through 7 are used to define the digester, letters “a” through “c” are used to define different operational conditions. Chapter 6.1 presents the WWTPs characterization and the expected and produced sludge volumes. This chapter also analyzes the effect of operational and design parameters on primary and waste activated sludge production and composition. Chapter 6.2 presents the characterization of the digesters. In order to categorize and compare the evaluated WWTPs in digester relevant parameters, the hydraulic retention time and the organic loading rate of the digester and its fluctuation were determined. Chapter 6.3 focuses on the characterization of digester performance. Specific evaluation points are volatile solids stabilization fraction, specific biogas production, solids removal rate and biogas production rate. The original values of the presented results are summarized in Annex 13.7.

6.1. WWTP CHARACTERIZATION

This chapter describes the characteristics of each evaluated wastewater treatment plant. It focuses on the parameters relevant to production of primary and waste activated sludge.

6.1.1. PRIMARY SLUDGE

Primary sludge is the biggest energy carrier for the anaerobic digestion process. Large amounts of primary sludge and high total volatile solids fractions are desirable for high biogas production. The surface overflow rate (SOR) (Eq. 43) is an indicator of the primary sludge settling tank design; the higher the SOR the shorter the hydraulic retention time in the primary settling tank and carbon removal decreases. Low SORs at around $20 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ are ideal for large primary sludge masses while high SORs at $50 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ warrant a high concentration of carbon in the aeration tank for improved denitrification. Figure 13 presents the surface overflow rate in the primary settling tank for each analyzed WWTP as box plots. The dotted line indicates the typical design parameters between $20 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ and $50 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ (METCALF & EDDY, 2014). The presented results consider all weather conditions.

WWTP and Digester Analysis

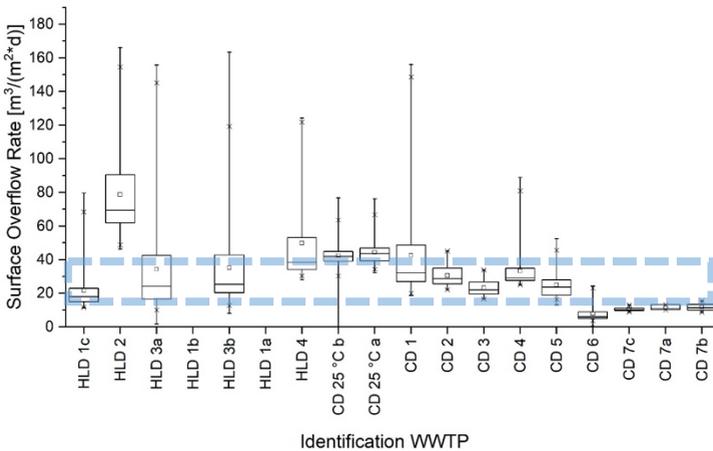


Figure 13: Box plot of the surface overflow rate in the primary settling tank for each evaluated WWTP compared to typical design parameters.

Most analyzed PSTs operate within design parameters, marked with the dashed line. Notable exceptions are WWTP CD 6, CD 7 and HLD 1, which present a very low SOR and conversely high HRT in the PST. WWTP HLD 2 presents a very high SOR and conversely short HRT in the PST. WWTP CD 25 °C has the second highest median SOR, followed closely by WWTP HLD 4, both at about 40 m³/(m²*d). WWTPs CD 1, 2 and 4 are within the lower half of the design recommendations at a median of about 30 m³/(m²*d). WWTPs CD 3, CD 5 and HLD 3 present a median SOR between 20 m³/(m²*d) and 25 m³/(m²*d) just inside the lower end of typical design recommendations. Significant variation towards increased SOR can be associated with rain events.

WWTP and Digester Analysis

Based on the SOR, WWTPs HLD 1, CD 6 and CD 7 should present high COD removal in the PST, high masses of primary sludge and increased biogas production from it, while WWTPs CD 25 °C and HLD 2 would present lower COD removal, lower masses of PS lower specific biogas production from PS. The other analyzed WWTPs would lie in between. Overall, the analysis showed that most WWTPs operate at relatively low SOR (compare Figure 5), resulting in expected high biogas production from primary sludge. However, a definitive statement on biogas production potential is not possible without experimental analysis. A significant aspect of sludge quality is the sludge management on the WWTP, specifically how and when the sludge removal occurs.

In the case of WWTPs CD 3, CD 5, CD 6 and CD 25°C, primary sludge thickening takes place directly in the PST. WWTP HLD 4 presents an equalization tank between the PST and the digester, however thickening partially takes place in the PST. On WWTPs CD 2, CD 4, CD 7, HLD 2 and HLD 3, primary sludge thickening occurs in a separate settling tank. WWTP HLD 1 thickens the PS and WAS mechanically, while WWTP CD1 recirculates the WAS to the primary settling tank and thickens the combined sludge statically in the collector of the primary settling tank. (Table 13, Table 14 and Table 15).

Figure 14 presents the median total solids (TS) (light brown columns) and total volatile solids (TVS) (dark brown columns) fraction of the primary sludge, as well as the median TVS fraction (black numbers).

WWTP and Digester Analysis

The common solids content for primary sludge (according to METCALF & EDDY, 2014) is marked with the striped line.

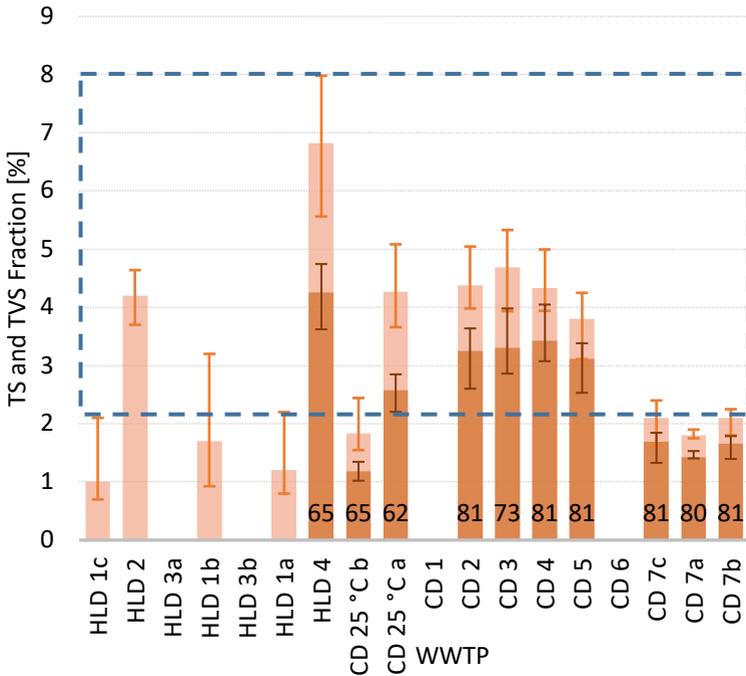


Figure 14: Median TS [%M] (light brown columns), TVS [%M] (dark brown columns) and TVS [%TS] (black numbers) of the primary sludge as well as common values for the solids content in primary sludge

There is no available data on the solids content of primary sludge for WWTPs HLD 3, CD 1 and CD 6. These WWTPs do not measure PS solids concentration. WWTPs HLD 1 and HLD 2 only measure the total solids fraction of the primary sludge. WWTPs HLD 2, HLD 4, CD 25 °C, operational condition a, and CD 2 through CD 5 present typical values

WWTP and Digester Analysis

for TS content. However, the TVS fraction (as % of TS) for WWTPs HLD 4 and CD 25 °C is relatively low. This indicates presence of inorganic substances, e.g. clay and sand from pipelines. WWTPs HLD 1 and CD 7 present a relatively low TS fraction in the primary sludge. These values originate from sampling location and sludge removal strategy from the PST.

WWTP CD 25 °C under operational condition “b” does not reach the typical TS fraction. However, its surface overflow rate does not reflect this condition. It is associated with sludge quality! This WWTP receives the sludge from a water treatment plant (WTP). The main difference between operational condition “a” and “b” is an alteration of the coagulant type used on the WTP. The WTP coagulant under condition “a” was iron based, while the coagulant under condition “b” was a poli-aluminum-chloride. The lower TS fraction reflects directly on the digester, decreasing the hydraulic retention time. This justifies the separation in two distinct operational settings.

WWTP HLD 4 presents a relatively high TS fraction in the primary sludge. This can be associated with high inorganic fraction in the sludge during rain events. In the analyzed period, 15 measurements for primary sludge were available, of which seven taken during a rain period. Analysis of primary sludge data showed significant inconsistencies compared to the sludge fed to the anaerobic digester, eliminating this sludge stream from the investigation.

WWTP and Digester Analysis

WWTP CD 7 is equipped with static pre-thickener that receives primary sludge from the primary settling tank where it is further thickened in combination with WAS before being fed to the anaerobic digester. A similar situation occurs on WWTP HLD 1. There, the primary sludge is further thickened through mechanical thickening after the PST. Thus, the information available on the total solids concentration for the primary sludge of CD 7 and HLD 1 does not fully characterize the primary sludge fed to the anaerobic digester. However, based on the available data, it is possible to determine the primary sludge load to the digester.

WWTP HLD 3 is equipped with static pre-thickener that receives primary sludge from the PST and pre-thickened waste activated sludge. However, there are no TS or flow measurements of primary sludge and thus it is only possible to infer the primary sludge loading through the difference between WAS and total raw sludge. There is also no total solids or flow measurement on the primary sludge of WWTP CD 1 and CD 6.

WWTPs HLD 2 and CD 2 through CD 5 present similar values of primary sludge quality. Here, a relatively standard biogas production is expected. Sludge quality likely improves due to relative automation of sludge removal from the PST. With exception of WWTP CD 5, primary sludge removal occurs in regular intervals, time controlled on WWTPs HLD 2, CD 3 and CD 4, and event oriented on WWTP CD 2.

WWTP and Digester Analysis

No correlation between the total solids fraction and the surface overflow rate of the primary settling tank was identified (see Annex 13.5). Overall, information on primary sludge is relatively poor or inexistent. Sampling has little standardization and measurements reflect momentary properties, not daily averages. PST design properties are an auxiliary parameter to identify primary sludge quality. To reach better understanding of the primary sludge quality and allow detailed prediction of biogas production an improvement in the sampling method is necessary. E.g., total COD measurement of sludge quality could be included on a regular basis (SCHAUM et al., 2016).

6.1.2. WASTE ACTIVATED SLUDGE

Sludge age defines the ratio between cells in the activated sludge process and the cells removed from the activated sludge process (Eq. 45). The excess cells are fed to the anaerobic digester. Figure 15 presents the sludge age, for each evaluated treatment condition as a box plot, as well as typical design values for different treatment goals. Design sludge age for carbon removal lies below 5 days of sludge age, while an activated sludge process with nitrification and denitrification requires about 11 days. Sludge ages above 25 days indicate an aerobically stabilized activated sludge. The last case means that the sludge is already degraded and is unlikely to degrade further, not contributing significantly to biogas production. Waste activated sludge degradability decreases with sludge age increase (GOSSET & BELSER, 1982).

WWTP and Digester Analysis

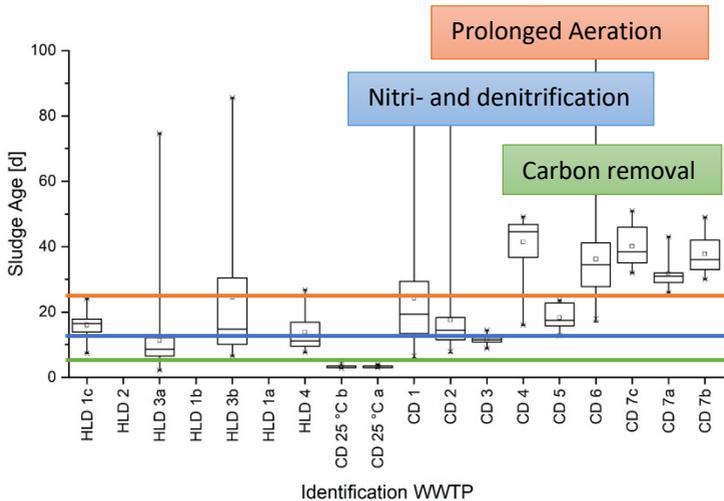


Figure 15: Sludge age of activated sludge in aeration tank and its typical design values for carbon removal, nitrogen removal and prolonged aeration

WWTPs CD 4, CD 6 and CD 7 present average and median sludge ages significantly above 25 days. WWTP CD 1 and CD 5 present slightly higher sludge ages than necessary at about 18 days. In these cases, the biogas potential decreases and an unnecessary energy waste occurs due to prolonged aeration. WWTP CD 2, CD 3, HLD 1, HLD 3 and HLD 4 present sludge ages typical for the nitrification and denitrification process while WWTP CD 25 °C has an average sludge age of 3 – 3,5 days, typical for WWTPs that only remove carbon. It is noteworthy, that WWTP CD 2 purposely has a high volatile solids removal in the primary settling tank and adds an external carbon source to the activated sludge process to guarantee the

WWTP and Digester Analysis

denitrification process. Thus, it is expected, that the WAS of WWTP CD 25 °C produces more biogas given its shorter sludge age. The smallest biogas production from WAS is expected on WWTPs CD 4, CD 6 and CD 7.

The WWPT operator has significant influence on the sludge age, given he makes the decision of removing WAS or not. Significant variation in the sludge age can be associated with the operational conditions on the WWTP. E.g., during weekends WAS is not removed, being compensated on Mondays. Practically none of the WWTP operators considered sludge age relevant, the most relevant parameter for operation was the performance of nitrification and denitrification process.

Next to the sludge age the total volatile solids fraction of the waste activated sludge can be a parameter to indicate waste activated sludge quality. Figure 16 presents the total volatile solids fraction of the waste activated sludge and the typical values found on WWTPs. Typical values lie between 60 % TVS for stabilized WAS and 70 % for fresh WAS.

WWTP and Digester Analysis

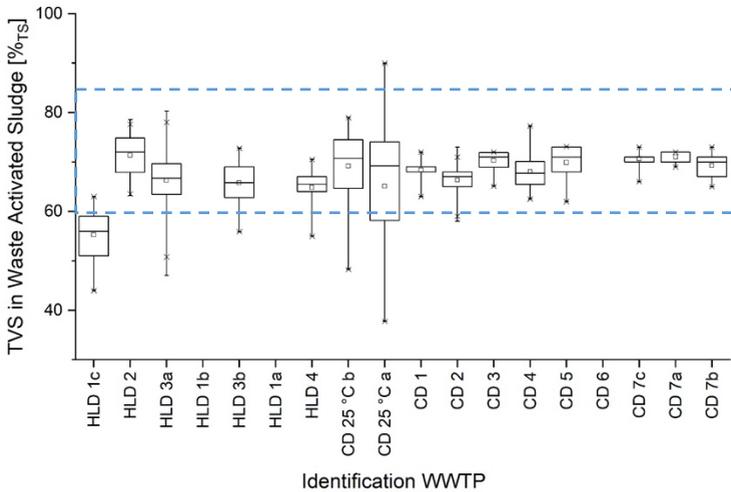


Figure 16: TVS fraction of waste activated sludge and common TVS values

The TVS in the WAS for the evaluated WWTPs varied between 65 % and 72 %, with the exception of the TVS from WWTP HLD 1 under operational condition “c” at less than 60 %. The analysis of TVS over sludge age for different WWTPs did not show any direct correlation (See Annex 13.5). Registered TVS values lie within the expected values.

Waste activated sludge characterization typically has good quality and focuses on guaranteeing good nitri- and denitrification performance in the activated sludge process. However, there is no significant focus on improving sludge age to reach increased biogas production. Sludge age would be a good auxiliary parameter to

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identify WAS biogas production potential and general energy efficiency on the WWTP.

6.1.3. RAW SLUDGE

Raw sludge is the combination of primary sludge and waste activated sludge. It is the most available sludge quality reference, and thus the most used one. It serves as a quality reference to characterize digester loading-rate. Figure 17 presents the total solids fraction (green) and total volatile solids fraction (blue) fed to the evaluated anaerobic digesters. Figure 18 presents the volatile fraction of total solids (TVS_{%TS}).

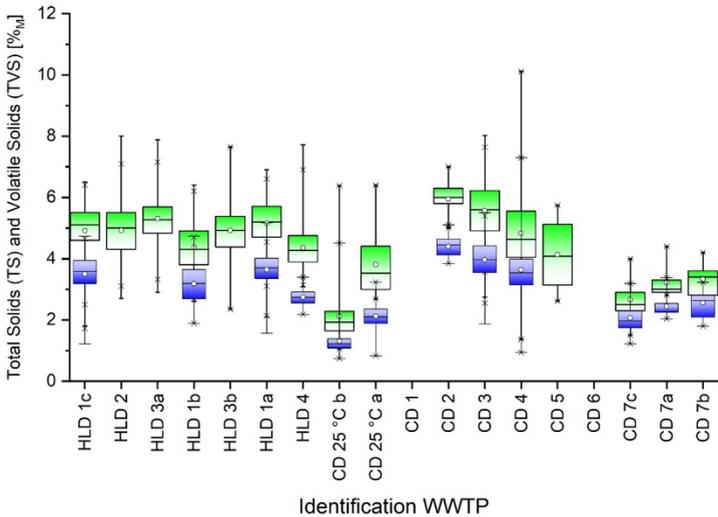


Figure 17: Total solids fraction (green) and total volatile solids fraction (blue) fed to the anaerobic digesters

WWTP and Digester Analysis

Several of the analyzed WWTPs present a high total solids fraction at the inflow to the digester. WWTPs HLD 1, HLD 2, HLD 3, CD 2, CD 3 and CD 4 present median TS concentration above 5 % and WWTP CD 2 even reaches a median TS content of 6 % at the inflow to the digester. WWTPs HLD 4 and CD 5, present median TS content at the inflow above 4 %. All these WWTPs are equipped with mechanical WAS thickening. WWTP CD 25 °C and CD 7 present lower TS fractions at the inflow to the digester. Both these WWTPs are only equipped with static thickeners. This TS fraction is typical for this type of thickening technology. WWTPs CD 1 and CD 6 do not regularly measure TS at the inflow to the digester. For the latter two digesters, the only measurements to characterize the digester and its performance are inflow, hydraulic retention time and biogas production.

WWTP and Digester Analysis

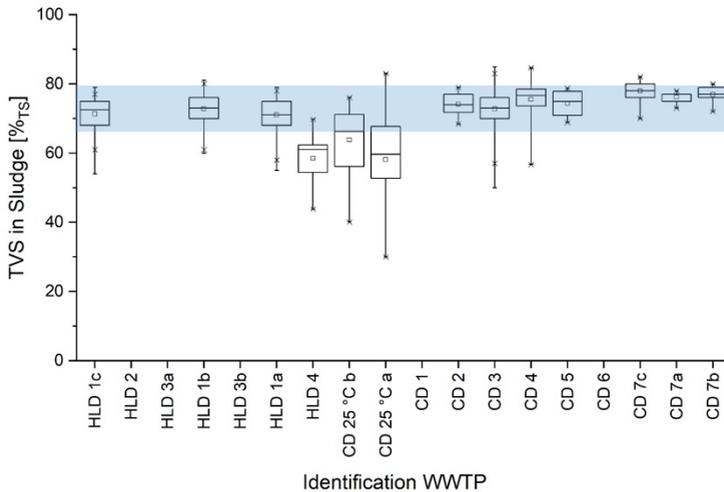


Figure 18: Total Volatile Solids at inflow digester, blue stripe indicates literature values (Table 9)

WWTPs HLD 2, HLD 3, CD 1 and CD 6 do not regularly register the total volatile solids fraction at the inflow to the digester.¹² Low TVS_{%TS} fractions for WWTP HLD 4 and CD 25 °C propagate from the low TVS content in the primary sludge (Figure 14).

Even though raw sludge characteristics are more readily available, there is no significant standardization on sampling, resulting in localized instead of average information. However, given the data

¹² Consequently, for these cases it is not possible to determine the organic loading rates. However, for WWTP HLD 2 and HLD 3, TVS fraction can be estimated based on literature data and values from measuring programs.

density, for the purpose of this work, these values were selected for processing and further analysis.

6.2. ANAEROBIC DIGESTER CHARACTERIZATION

This chapter characterizes the anaerobic digesters regarding its hydraulic retention time and organic loading rate. It also highlights some operational characteristic, showing differences between digesters operated with higher and lower degrees of automation.

6.2.1. HYDRAULIC RETENTION TIME OF THE PRIMARY ANAEROBIC DIGESTER(S)

The most traditional design parameter for anaerobic digesters is the hydraulic retention time (HRT or τ_m). Figure 19 presents the hydraulic retention times for the analyzed WWTPs as box plots organized from the lowest to the highest HRT.

WWTP and Digester Analysis

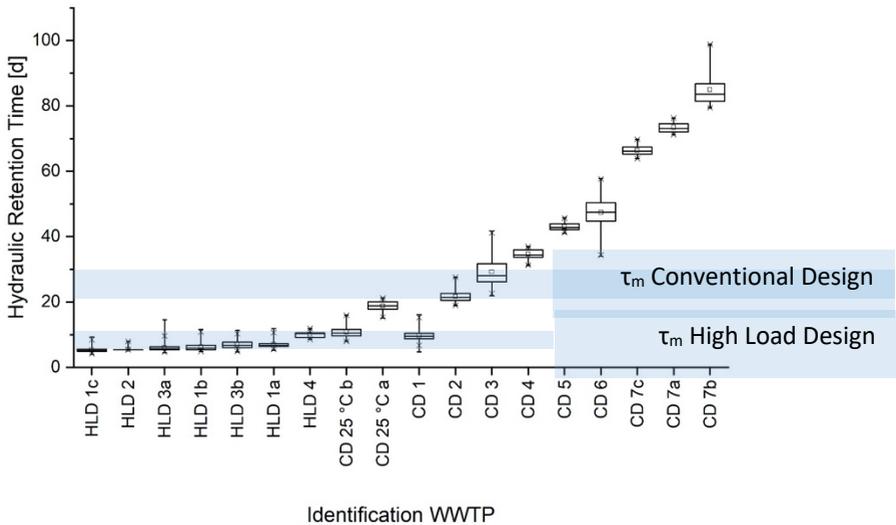


Figure 19: Hydraulic retention time of the evaluated digesters and typical design recommendations for conventional (15 d – 28 d - top rectangle) and high load anaerobic digesters (bottom rectangle 5 – 10 d)

WWTPs HLD 1, HLD 3, CD 25 °C and CD 7 have marked changes in the inflow regime to the digester over time, leading to more than one set of data for the same anaerobic digester. HLD 1 and CD 7 showed three statistically different hydraulic retention times. CD 25 °C and HLD 3 showed two statistically different HRTs. (ANOVA Analysis in Annex 13.6)

Originally, the high load digester design proposed hydraulic retention times between 5 and 7 days (Table 11). More recently, considering the expansion plans of one WWTP, design HRT expanded to up to 10

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days HRT (STERNAD et al., 2016). The evaluated results mostly stayed within the design parameters. The lowest observed HRT was on WWTP HLD 1 for operational condition “c” at 5.1 days in the median, while operational conditions “b” and “a” presented 5.9 d and 6.8 d as median HRTs respectively. WWTP HLD 2 presented a very steady HRT of 5.4 days. This steadiness is part of the operational conditions; the digester runs at 5.4 days of HRT and any excess sludge bypasses directly to the secondary digesters. WWTP HLD 3 under operational conditions “a” and “b” presented median HRTs of 5.8 days and 6.7 days respectively. WWTP HLD 4 presented a median HRT of 10.4 days. The 25 percentile and 75 percentile from the HRT do not vary more than 10 % compared to the median. All HLDs maintain a minimum HRT of about 5 days. The maximum HRT does not surpass 12 days. This relatively stable feeding regime is reached through an equalization tank before the digester.

Regular digesters design proposes HRTs of about 20 days (Table 11). However, the observed hydraulic retention times presented a range of operational conditions. WWTP CD 1 presented the lowest measured HRT at about 10 days. This WWTP is equipped with two digesters originally planned to operate in parallel. The operator shifted digester operation from parallel to serial. Since digestion under serial operation showed better performance, the operator decided to keep the digester system in series. Both digesters are heated.

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WWTP CD 25 °C is a conventional unheated digester. Under operational condition "b", it presents a median hydraulic retention time of 10.5 days. This originates from the lower thickening performance of the primary settling tank. The operator has no option but to feed the thinner sludge into the digester. To change this condition, significant investment measures would have to be taken on the WWTP. Under operational condition "a", this issue was not present and HRT was at 19 days.

WWTP CD 2 practically runs at perfect design conditions with 21 days HRT in the median. The large size of the WWTP allows a very steady sludge feeding and significant automation. WWTPs CD 3 and CD 4 have slightly higher than standard design conditions and present HRTs of 28 days and 34 days in the median. The operation of WWTP CD 3 does not particularly focus on sludge management, resulting in larger variation of the hydraulic retention time. WWTPs CD 5, CD 6 and CD 7 operate significantly above typical design conditions. Given these WWTP only have one anaerobic digester, there is no direct and simple operational alternative to reduce the high digestion times.

The 25 percentile and 75 percentile from the HRT of conventional digesters also does not vary more than 10 % compared to the median. However, the HRT ranges from 10 to 84 days. The difference in HRTs of the different WWTPs is expected. It is relevant to consider, that high load digesters are relatively new. The first HLD started operation in 1994, the most recent one in 2018. Their design already

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included effective thickening processes and relatively secure population development predictions, while the regular digesters can be significantly older and prone to historic design developments. Oversized population growth expectancy, unplanned industrial development and safety factors during the design of anaerobic digesters have resulted in significantly higher HRTs in the common anaerobic digesters compared to the original design recommendations. These results are also consistent with other studies. E.g. in the State of Baden-Württemberg in Germany over 90 digesters were evaluated regarding its HRT. It was observed that on average 90 % of the digesters have a higher HRT than the original design (WAELENS; QUINTANA, 2016).

6.2.2. DIGESTER LOADING RATE

The concentration of the organic sludge fed to the digester and hydraulic retention time determine the organic loading rate (Eq. 47). A thick sludge with high organic content and short hydraulic retention times in the digester will contribute to high organic loading rates, while a thin sludge with low organic content or long hydraulic retention times in the digester will result in low organic loading rates.

The sludge loading rates can be determined similarly to the organic loading rates, applying the total volatile solids concentration instead of the total solids concentration. Figure 20 presents the sludge loading-rate and organic loading-rate of the analyzed digesters. On some WWTPs, the specific load of primary sludge and WAS is also

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registered. The specific sludge loading rates of primary sludge and WAS to the digester and when available the organic loading rates of primary sludge and WAS were also determined.

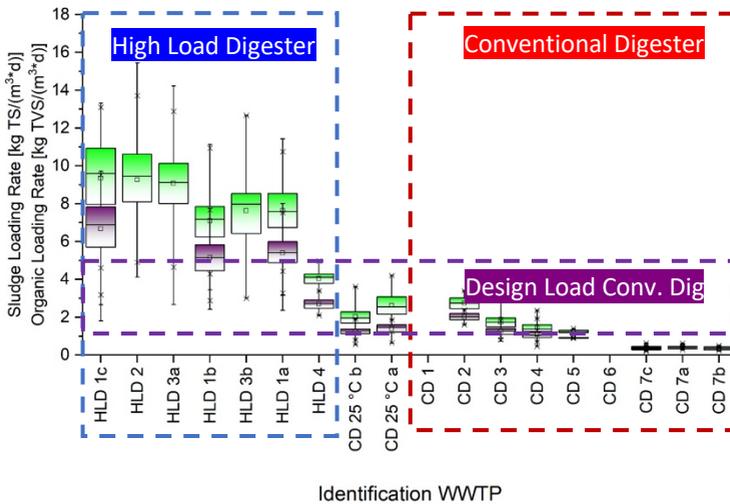


Figure 20: Sludge loading rate (green) and organic loading rate (purple) to the digester

In the red box, WWTPs CD 2 – CD 7 operate at or above regular hydraulic retention times (Figure 19). WWTP CD 7 presents the highest hydraulic retention time (66-83 days) and the lowest loading rate at $0.4 \text{ kg}_{\text{TS}}/(\text{m}^3 \cdot \text{d})$ or $0.3 \text{ kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$, somewhat below design loads. WWTP CD 6 does not have detailed data on the solids load to the digester, however short term measurements showed an inflow to the digester of less than $3.0 \%_{\text{TS}}$ resulting in solids loading rates of less than $1 \text{ kg}_{\text{TS}}/(\text{m}^3 \cdot \text{d})$. The organic loading rate varies between 1.0

WWTP and Digester Analysis

$\text{kg}_{\text{TVS}}/(\text{m}^3\cdot\text{d})$ and $2.0 \text{ kg}_{\text{TVS}}/(\text{m}^3\cdot\text{d})$ for digesters CD 3 to CD 5. The median loading rates of WWTPs HLD 1-4 vary between $4.1 \text{ kg}_{\text{TS}}/(\text{m}^3\cdot\text{d})$ and $9.6 \text{ kg}_{\text{TS}}/(\text{m}^3\cdot\text{d})$ or $2.7 \text{ kg}_{\text{TVS}}/(\text{m}^3\cdot\text{d})$ to $6.9 \text{ kg}_{\text{TVS}}/(\text{m}^3\cdot\text{d})$, characterizing the high load digestion.

WWTP CD 25 °C “a” and “b” have similar organic loading rates but WWTP CD 25 °C “a” has double the hydraulic retention time in the digester compared to operational condition “b”. This originates from the low TS concentration in the primary sludge. Here, it is very clear to observe, that a high organic loading rate does not always reflect an ideal operational condition.

WWTP CD 1 shifted operation from parallel to serial reducing hydraulic retention time in the first and second digesters. There is no extensive data on solids concentration to digester CD 1, however average samples over 2 weeks showed a TS to the digester of about 3 %, resulting in a sludge loading rate of about $3 \text{ kg TS}/(\text{m}^3\cdot\text{d})$ or $2 \text{ kg TVS}/(\text{m}^3\cdot\text{d})$.

6.3. SUMMARY WWTP AND DIGESTER CHARACTERISTICS

The characterization of the WWTPs showed that the evaluated WWTPs:

- surface overflow rates vary between $10 \text{ m}^3/(\text{m}^2\cdot\text{d})$ and $40 \text{ m}^3/(\text{m}^2\cdot\text{d})$ and overall the primary settling tanks are relatively big

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- reach (activated) sludge ages from 3 days to over 25 days
- cover a range of hydraulic retention times in the digester from 5 days up to 85 days,
- have organic loading rates ranging from $0.3 \text{ kg}/(\text{m}^3 \cdot \text{d})$ to $7.0 \text{ kg}/(\text{m}^3 \cdot \text{d})$

WWTP CD 6 and CD 7 present the highest hydraulic retention times in the digester, as well as the lowest surface overflow rates in the primary settling tank and highest sludge age for the activated sludge. The digester loading rates are very low considering the large digester volume. WWTP CD 7 showed a very high fraction of primary sludge in the overall organic loading rate to the digester. This shows consistency with the results from sludge management, where the low surface overflow rate increases primary sludge mass and high sludge age reduces WAS mass.

The digesters of WWTP CD 6 and CD 7 are significantly larger than necessary. This results in very high hydraulic retention times. This system will likely reach complete degradation of the inflowing degradable sludge fraction. However, oversized digesters (and WWTPs) will have higher energy demand, e.g. to heat or mix the digester. The high primary sludge fraction indicates that the digesters of WWTP CD 6 and CD 7 will show high sludge reduction and specific biogas production. The high hydraulic retention time should reflect low specific reaction rates.

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WWTP CD 5 is slightly closer to design parameters. It still has a very large anaerobic digester, resulting in relatively low organic loading rates. It is expected to perform slightly worse than WWTP CD 6 and CD 7 regarding sludge reduction and specific biogas production and expected to perform better regarding the specific reaction rates.

At about 35 days HRT, WWTP CD 4 has a slightly larger anaerobic digester than design recommendations. It presents a primary settling tank within design recommendations. Its activated sludge age is rather high. This results in a primary sludge fraction of about 75 % in the organic loading rate to the digester. The high PS content should result in effective solids stabilization fractions and high specific biogas production.

Even though WWTP CD 3 is a conventional WWTP, it has a special feature: it receives highly concentrated dissolved organic material from an industry. This co-substrate feeds directly into the anaerobic digester. The small volume of industrial co-substrate does not affect the determination of the hydraulic retention time. The total volatile solids fraction only increases slightly. However, the sludge COD increases. With its particularly low surface overflow rate and average sludge age, a relatively large primary sludge fraction is expected. The primary sludge fraction reaches 63 % of the total organic loading rate to the digester. Given the energy rich substrate fed to the digester, higher than usual specific biogas production is expected, solids stabilization fractions according to the sludge composition are

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expected. I. e. primary sludge degrades better than WAS. Considering the high PS fraction, good TVS stabilization is expected.

WWTP CD 2 presents operation conditions very close to the design optima, its digester runs at about 20 days HRT, it has an organic loading rate of about $2 \text{ kg}/(\text{m}^3 \cdot \text{d})$ and the surface overflow rate and sludge age are within design recommendations. Compared to the design standards, WWTP CD 2 is expected present a slightly better performance considering that:

- 66 % of the organic loading rate originates from primary sludge;
- The WWTP operation focuses on removing as much carbon as possible in the primary settling tank for higher biogas production.
- A carbon source is added to the aeration tank when needed (about 0.1 % of the inflow organic load); and
- This WWTP receives co-Substrate from a food producing company, which could result in slightly higher biogas production than a typical municipal WWTP.

WWTP CD 1 is a particularly interesting case study. It is composed of a conventional anaerobic digester system that shifted operation from parallel to serial. The hydraulic retention time in the primary digester is of about 10 days and the estimated organic loading rate is at about $2 \text{ kg}/(\text{m}^3 \cdot \text{d})$. The SOR on the WWTP is within design

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recommendations. However, the sludge age lies slightly above standard. It is particularly tricky to present estimates towards the expected performance of the anaerobic digester, given that besides the local sludge production this WWTP also receives the sludge from a second WWTP, representing about 20 % of the solids fraction added to the digester.

The digester of WWTP CD 25 °C operates at ambient temperature. The performance evaluation of operational condition “a” characterizes a digester with 20 days HRT operated at temperatures of about 25 °C, while the operational condition “b” illustrates the consequences of low hydraulic retention time associated with low organic loading rate. SORs are slightly higher than on most other evaluated WWTPs, however still very much inside design recommendations. Activated sludge age is significantly lower than from the other WWTPs given the different treatment objective of carbon removal instead of nitrogen removal. Digester loading rates are similar to WWTPs CD 3, CD 4 and CD 5. A lower overall performance is expected given the lower operating temperatures.

In the analysis period, WWTP HLD 4 operated two high load digester in series. It is the high load digester with the highest hydraulic retention time at about 10 days. The SOR on this WWTP lies at about $40 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ and is relatively high. This could be an indicator of high fixed solids fraction in the primary sludge. The sludge age lies at about 11 days.

WWTP and Digester Analysis

WWTP HLD 3 operates two high load digesters in series. Two different operational conditions were identified. The HRT for operational condition “a” lies at 5.8 days in the median while in case “b” it is 6.7 days. The SOR for both conditions is practically the same and is within design expectations. However, the sludge age for “a” is about 9 days while for “b” it is at 14 days. A higher activated sludge age could be associated with a smaller fraction of solids in the WAS resulting in a decrease of the sludge volume and thus higher hydraulic retention time in the digester. The sludge loading rate varies from 8.1 kg TS/(m³*d) to 9.0 kg TS/(m³*d). With an estimated volatile solids fraction of 70 %, the organic loading rate lies at about 5.6 kg TVS/(m³*d) to 6.4 kg TVS/(m³*d).

WWTP HLD 2 presents a very high SOR and a low fraction of primary sludge in the total sludge. The WAS organic solids fraction is slightly higher than from the other WWTPs. The primary sludge and WAS are further thickened before being fed to the digester. This WWTP operates at a very steady HRT of 5.4 days. The sludge loading rate was at 9.5 kg TS/(m³*d), with an estimated organic fraction of 70 % the organic loading rate is estimated at about 6.6 kg TVS/(m³*d).

WWTP HLD 1 presents three different operational conditions for the anaerobic digester operation. WWTP data were only available for operational condition “c”. The other two operational conditions only present data from the sludge treatment phase. The identified SOR for operational condition “c” was particularly low and the sludge age

WWTP and Digester Analysis

relatively high. A high primary sludge fraction is expected, however this was not the case, the primary sludge fraction was below 50 % of the organic load. The low PS fraction originates in the sludge removal strategy. The PST does not remove thick sludge cake. There is solely a mechanical thickening. The sludge loading rates for conditions “a” and “b” at about 7-8 kg TS/(m³*d) are comparatively lower than for condition “c” at almost 10 kg TS/(m³*d). A relatively low TVS removal and biogas production rate are expected for condition “c”, given the low fraction of primary sludge and the high sludge age in the aeration tank.

The analyzed WWTPs present a variation of solids concentration at the inflow between 2 % TS and 9 % TS and a solids composition that is influenced by primary and waste activated sludge. WWTPs HLD 1 to 4 operate under higher load conditions when compared to WWTPs CD 1-7 and WWTP CD 25 °C. Aiming at the analysis of single rate kinetic approach the evaluated data presented a wide range of information.

7. DIGESTER PERFORMANCE

The primary goals of anaerobic digestion are to reduce odor, stabilize the sludge and reduce the sludge mass to allow easier, safer and more stable sludge disposal. A well performing digester will reduce a significant amount of the total volatile solids. As a positive side effect, this will result in biogas production. This chapter investigates the effectiveness of the total volatile solids removal in the analyzed digesters through the evaluation of the parameter TVS stabilization and specific biogas production per organic substrate added. Furthermore, this chapter evaluates the reactor efficiency and specific performance by analyzing the total solids removal rate and the specific biogas production rate. The original values of the presented results are summarized in Annex 13.9.

7.1. DIGESTER EFFECTIVENESS: SUBSTRATE DEGRADATION

7.1.1. BIOGAS PRODUCTION

The easiest method to evaluate substrate degradation is by measuring biogas production. A large production of biogas correlates to a large solids removal or substrate stabilization fraction. The quality, or biodegradability, of the total volatile solids added to the reactor significantly influence substrate degradation performance. E.g., the more primary sludge added to the reactor, the higher is the expected biogas production. Figure 21 presents the biogas production per total volatile solids added, as a function of the median

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hydraulic retention time for one digester (red diamonds) and two digesters in series (blue squares). The dotted lines presents typical values for biogas production from wastewater sludge. The brackets represent the error propagation from the determination of these median values.

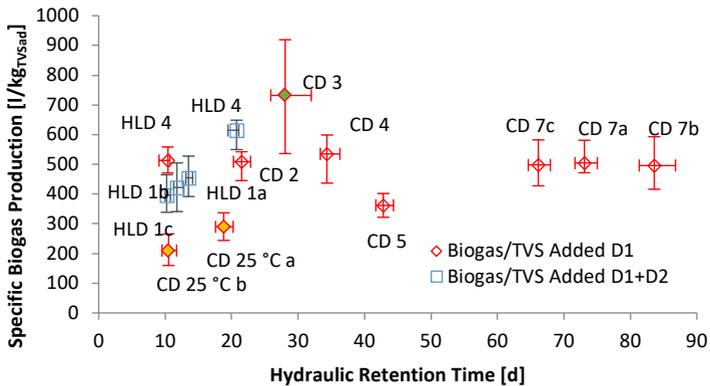


Figure 21: Biogas production per total volatile solids added in one digester or two digesters in series

The primary digester of WWTPs CD 2, CD 4, CD 7 and HLD 4 presented similar median biogas productions per TVS added, varying between 496-526 l/kg_{TVS_{ad}}. The organic load from PS in these WWTPs exceeds 65 % of the total load in all cases. This means, 65 % of the total organic solids load added to these digesters originates from primary

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sludge and only 35 % of the total organic solids load originates from waste activated sludge.

The total biogas production for WWTP CD 3 is significantly higher than average. This can be explained by the fact that WWTP CD 3 receives high-energy content co-substrate, which is likely not measured through total solids and total volatile solids analysis due to high vapor pressure of the substance, resulting in a biased result of higher biogas yield per TVS added. This result shows the importance of the type of measurement to determine reactor performance. The result is marked with green filling to differentiate itself from the other biogas production data and is not used to calibrate the current model. It is kept to demonstrate data sensitivity. Here, COD measurements would likely result in better insight to reactor performance, as suggested by Schaum et al. (2016). Unfortunately, none of the WWTPs currently measure COD in the sludge and solid phase.

WWTP CD 5 presents a median biogas production of 468 l/kg_{TVS_{ad}}. WWTP CD 25 °C operates at an average of 25 °C, resulting in lower biogas production in general. Nevertheless, condition “a” presents a significantly higher specific biogas production (290 l/kg_{TVS_{ad}}) than in “b” (209 l/kg_{TVS_{ad}}). Organic PS loads are respectively 72 % and 53 %. WWTPs HLD 2, HLD 3, CD 1 and CD 6 do not present volatile solids

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concentration measures. Thus, it is not possible to establish this parameter for these WWTPs.

The biogas production for WWTP HLD 4 after two tanks in series is at 613 l/kg_{TVS_{ad}}. The second heated digester contributed with about 100 l/kg_{TVS_{ad}}, or 16 % of the total. WWTP HLD 4 presents an insight to the efficiency of biogas production for two tanks in series.

For WWTP HLD 1 only the combined biogas production of two digesters in series is measured. WWTP HLD 1 presents a relatively low specific biogas production compared to the other WWTPs. Organic loads from primary sludge are not available. However, based on sludge load data, these are estimated at 40 % to 50 % of the total organic load. Conditions “a”, “b” and “c” present a decreasing median biogas production from 454 l/kg_{TVS_{ad}}, 421 l/kg_{TVS_{ad}} to 395 l/kg_{TVS_{ad}}. Here, it is relevant to note, that the organic loading rate increased significantly from condition “b” (5.0 kg TVS/(m³*d)) to condition “c” (7.0 kg TVS/(m³*d)). The hydraulic retention time in the primary digester decreased from “a” (6.8 days or 13.6 days for two tanks in series) to “b” (5.9 days or 11.8 days for two tanks in series) down to condition “c” at 5.1 days (or 10.2 days for two tanks in series).

7.1.2. VOLATILE SOLIDS REMOVAL

Next to the specific biogas production, the total volatile solids removal describes digester performance. Figure 22 presents the TVS

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removal in one digester (red diamonds full) and two digesters in series (blue squares full) for the evaluated WWTPs.

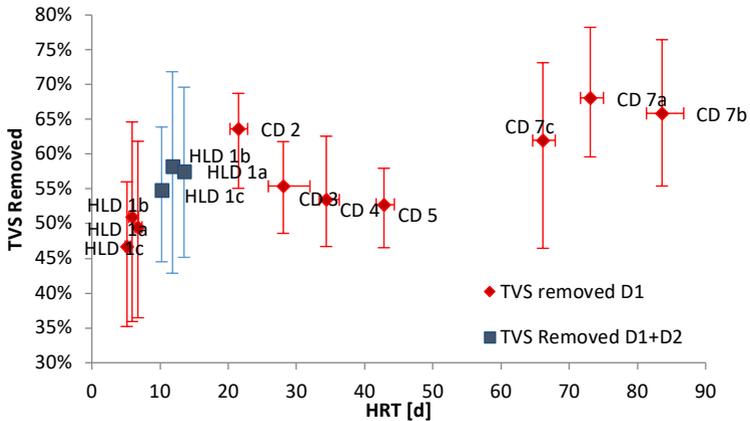


Figure 22: TVS removal in one digester and two digesters in series

It is possible to observe that the total volatile solids removal in digesters CD 2 and CD 7 were highest, reaching 62 % to 68 % of the input TVS mass. WWTPs CD 3, CD 4 and CD 5 presented TVS removal between 53 % and 55 %. Overall, the performance of sludge removal under operational condition HLD 1 "c" is slightly poorer than operational condition "a" and "b". WWTP HLD 1 presents relevant data regarding the sludge removal performance of two tanks in series. The second reactor contributed with about 12 % to 15 % of total solids removal.

WWTPs CD 3, CD 4, CD 5 and CD 7 present high SORs and primary sludge fractions above 60 %, what is indicative of high sludge

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reduction potential. WWTPs CD 4 and CD 7 present a high sludge age which has a negative effect on the degradable fraction of the WAS. WWTP CD 2 has a slightly higher primary sludge fraction than WWTP CD 3 and slightly lower sludge age, what might result in the better TVS removal fraction. WWTP HLD 1 presents a relatively low organic primary sludge fraction at 40 % to 50 % and has a particularly low TVS fraction in the WAS despite the appropriate sludge age, which can affect the total degradable solids fraction. WWTP HLD 1 “b” has a higher primary sludge fraction than under operational conditions “a” and “c” which might explain its better performance for the TVS removal.

The DWA M368 (2014) recommends that 85 % of the easily degradable solids decomposition in the digester is reached. This concept is quite practical, considering that not every sludge has the same biodegradability. The theoretical removal performance is determined, considering that 70 % of organic solids from the primary sludge are removed and 45 % of the organic solids from the WAS are removed. WWTPs CD 2, CD 3, CD 4, CD 5 and CD 7 have high primary sludge fractions that could indicate a high volatile solids reduction potential, while WWTP HLD 1, with its rather low primary sludge fraction, might not present the same biodegradability potential.

Based on the results of Figure 22; Figure 23 presents the normalized TVS removal in one digester and two digesters in series assuming 70

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% degradation of the organic fraction of primary sludge and 45 % degradation of the organic fraction of WAS.

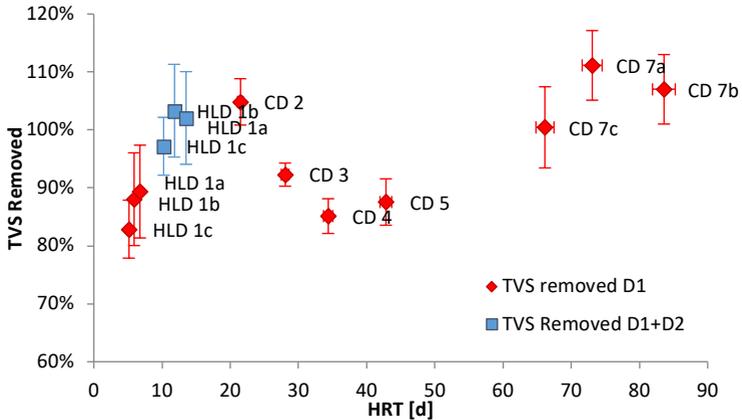


Figure 23: Normalized TVS removal in one digester and two digesters in series assuming 70 % degradation of the organic fraction of PS and 45 % degradation of the organic fraction of WAS

CD 2 and CD 7 presented digestion performances above the theoretical 100 % TVS removal value. This indicates higher biodegradability potential of either the PS or the WAS. CD 3, CD 4 and CD 5 are at or above the theoretically aspired 85 % TVS removal value. WWTP HLD 1 “a”, “b” and “c” reach 85 % of the theoretical degradation in the first anaerobic digester and about 100 % of the theoretical degradation values in the second anaerobic digester. In Figure 23, it is possible to observe that the TVS removal on WWTP HLD 1 in the first digester is similar to the TVS removal on WWTPs CD 3, CD 4 and CD 5, and that the combined TVS removal in the two

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digesters in series is similar to the TVS removal of WWTPs CD 2 and CD 7.

There is no information on the total volatile solids at the inflow to the digester for WWTP CD 1, CD 6, HLD 2 and HLD 3; thus, the parameters biogas per TVS added and total volatile solids removed cannot be determined for these cases.

In summary, reactor performance, as well as on the feed quality introduced to the digester, influence digester effectiveness regarding solids removal. Normalization of sludge quality allows an effective comparison of the actual digester performance. Here, the typical sludge removal values from literature are applied. Alternatively, when available, experimental data obtained from bio-methane potential tests (BMP tests) can be applied to determine 100 % biodegradability.

7.2. DIGESTER EFFICIENCY: REACTION RATES

7.2.1. BIOGAS PRODUCTION RATE

Next to the absolute effectiveness of the digester, digester performance evaluation occurs through biogas production rate and substrate removal rate. The reaction rates allow an insight to the digester efficiency. Figure 24 presents the specific biogas production rates in the first digester and second digester in series.

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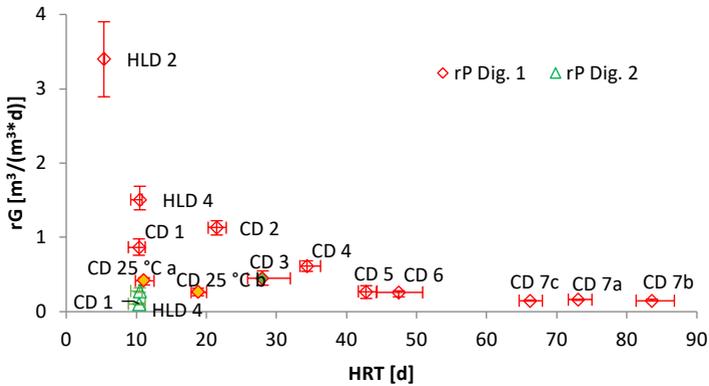


Figure 24: Biogas production rate in the first and second digester

It is possible to observe that the reaction rate increases with decreasing HRT. WWTP CD 7 at over 65 days of HRT presents the lowest biogas production rate at about $0.15 \text{ m}^3/(\text{m}^3\cdot\text{d})$. WWTPs CD 5 and CD 6 present biogas production rates of about $0.26 \text{ m}^3/(\text{m}^3\cdot\text{d})$ at HRTs slightly higher than 40 days. WWTPs CD 3 and CD 4 present reaction rates of $0.61 \text{ m}^3/(\text{m}^3\cdot\text{d})$ and $0.45 \text{ m}^3/(\text{m}^3\cdot\text{d})$ respectively, at HRTs around 28 to 34 d. WWTP CD 2 presents a specific reaction rate of $1.13 \text{ m}^3/(\text{m}^3\cdot\text{d})$ at 21 days HRT. WWTPs CD 1 and HLD 4 have similar HRTs of about 10 days in the first reactor. However, they present different reaction rates of $0.87 \text{ m}^3/(\text{m}^3\cdot\text{d})$ and $1.51 \text{ m}^3/(\text{m}^3\cdot\text{d})$ respectively. WWTP HLD 2 presents the highest reaction rate of $3.34 \text{ m}^3/(\text{m}^3\cdot\text{d})$ at 5.4 days HRT. At lower temperatures, WWTP CD 25 °C “a” presents a biogas production rate of 0.41

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$\text{m}^3/(\text{m}^3\cdot\text{d})$ and WWTP CD 25 °C “b” has a reaction rate of $0.26 \text{ m}^3/(\text{m}^3\cdot\text{d})$.

The biogas production in the second digester is significantly lower than in the first digester. WWTP HLD 4 presents a specific biogas production of $0.28 \text{ m}^3/(\text{m}^3\cdot\text{d})$ and WWTP CD 1 presents a specific biogas production of $0.10 \text{ m}^3/(\text{m}^3\cdot\text{d})$. The observed reaction rate in the second digester was of about 15 – 20 % of the reaction rate in the first digester.

The HRT of WWTP CD 5, CD 6 and CD 7 is significantly higher than the typical digester design recommends, however it allows insight into the effect of HRT on the reaction rate. The reduction of the HRT from WWTP CD 7 (85 to 65 days) did not significantly affect the reaction rate. The further reduction to WWTP CD 5 and CD 6 (about 45 days) resulted in double the biogas production rate. At HRTs of about 30 days (WWTP CD 3 and CD 4), the biogas production rate doubled or tripled again, when compared to the 45 days HRT. In the case of WWTP CD 2, the biogas production doubles again compared to the HRTs at 30 days and is almost 8 times higher than at 65 days. At 10 days HRT, HLD 4 was 30 % more efficient at producing biogas than WWTP CD 2 and 10 times more efficient than WWTP CD 7. At 5.4 days of HRT WWTP HLD 2 presents, by far, the most efficient biogas production performance reaching double the specific production from WWTP HLD 4 and 20 times the biogas production from WWTP

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CD 7. Most reaction rates increase with decreasing HRT, a notable exception is WWTP CD 25 °C from operational condition “a” to “b”.

In the case of WWTPs HLD 1 and HLD 2, the biogas production was measured only for the combined digester system and no data on the biogas production of the individual reactors was available. Figure 25 presents the total specific biogas production rate for the two combined digesters in series of WWTPs CD 1, HLD 2, HLD 3 and HLD 4.

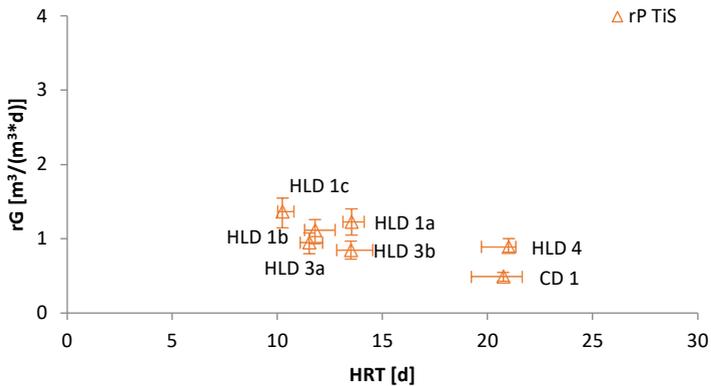


Figure 25: Total biogas production rate for two digesters in series

The apparent biogas production rate varied between $0.49 \text{ m}^3/(\text{m}^3\cdot\text{d})$ (WWTP CD 1) and $1.37 \text{ m}^3/(\text{m}^3\cdot\text{d})$ (WWTP HLD 1 “c”), higher apparent biogas production rates were observed at lower hydraulic retention times. WWTPs HLD 1 and HLD 3 have a shorter HRT for two digesters in series and a higher biogas production rate than WWTPs

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HLD 4 and CD 1. Similar to WWTPs HLD 4 and CD 1, as expected, the biogas production rate for the digesters of WWTPs HLD 1 and HLD 3 in the first digester is higher than in the second digester. Since both digesters are of the same size and have the identical inflow and outflow, the apparent biogas production rate for two digesters in series is actually the average of both reaction rates. I. e., for WWTP HLD 4, the biogas production rate in digester 1 is of $1.51 \text{ m}^3/(\text{m}^3\cdot\text{d})$ and in digester 2 is of $0.28 \text{ m}^3/(\text{m}^3\cdot\text{d})$, while the apparent specific biogas production is of $0.89 \text{ m}^3/(\text{m}^3\cdot\text{d})$. It is not possible, however, to infer the asymmetry of the individual specific biogas production.

7.2.2. TOTAL VOLATILE SOLIDS REMOVAL RATES

Considering it is likely that there is a direct proportionality between the biogas production rate and the (volatile) solids removal rate, this removal rate can give further insight to the degradation performance of the digesters. The advantage of evaluating solids and organic solids reaction rates is that intrinsic recalcitrant fractions of the solids measurement do not influence the observed results. This evaluation allows a comparison between WWTPs that only measure total solids and WWTPs that measure total as well as volatile solids. Figure 26 presents the substrate removal rates determined through total volatile solids measurements (Annex 13.7 presents the total solids removal rate).

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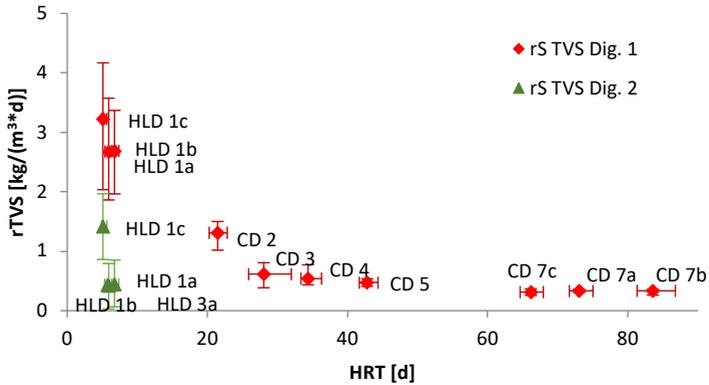


Figure 26: Substrate removal rates in the first and second digester considering TVS measurements

It is possible to observe that both, total solids (see Annex 13.7) and total volatile solids removal rates, present similar results for the individual digesters. Reaction rates are generally higher at lower hydraulic retention times. Reaction rates in the first digester ranged between 2.0 kg/(m³*d) and 3.2 kg/(m³*d) at HRTs of about 5 to 10 days. WWTP CD 2 at 21 days HRT reaches a reaction rate 1.3 kg/(m³*d). It gradually decreases for the other WWTPs, from 0.6 kg/(m³*d) to about 0.2 kg/(m³*d) at increasing HRTs. As in the biogas production rate, it is possible to observe that the reaction rate does not vary significantly between HRTs of 60 to 90 days. In the evaluated WWTPs 3.4 kg/(m³*d) was the maximum range of substrate removal observed.

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As expected from the apparent biogas production rates of WWTPs HLD 1 and HLD 3 (Figure 25) the TVS removal rate is higher in the first digester than in the second digester. For operational conditions HLD 1 “a” and “b”, as well as for both operational conditions of WWTP HLD 3 the TVS removal rate in the second digester is about 14 % to 17 % of the total load removal. Under operational condition HLD 1 “c”, the second digester contributes to 30 % to 40 % of the solids load removal, depending if the total volatile solids or the total solids fraction is considered. This last result shows that, if the first digester does not perform as expected the decomposition can occur in the second digester.

7.3. ANALYSIS DIGESTER PERFORMANCE

The digester performance evaluation showed that:

- The evaluated specific biogas production per added volatile solids varies between $395 \text{ m}^3/\text{kg}_{\text{TVS}_{\text{ad}}}$ and $614 \text{ m}^3/\text{kg}_{\text{TVS}_{\text{ad}}}$ with exception of WWTP CD 3 that receives a high-energy content co-substrate and WWTP CD 25 °C that operates at temperatures of 25 °C.
- The TVS removal fraction of all the evaluated digesters varied between 47 % and 68 %, however measured TVS removal fractions were within or above the recommended 85 % biodegradable TVS removal range.
- For WWTPs HLD 1 and CD 25 °C, specific biogas production and TVS removal fraction increase with the increase of HRT.

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- Sludge composition is fundamental to understand biogas production and solids removal potential.
- WWTPs with a higher fraction of primary sludge present a higher TVS removal, considering the typically higher degradability of primary sludge compared to WAS. The observed results are consistent with theory.
- For the individual digesters of WWTP CD 25 °C and WWTP HLD 1 it was possible to observe a dependency of the digester performance from the HRT, both operate below 20 days of HRT.
- The reaction rate of biogas production varied between $0.15 \text{ m}^3/(\text{m}^3\cdot\text{d})$ and $3.40 \text{ m}^3/(\text{m}^3\cdot\text{d})$, the reaction rate of TVS removal varied between $0.20 \text{ kg}/(\text{m}^3\cdot\text{d})$ and $3.30 \text{ kg}/(\text{m}^3\cdot\text{d})$ and as expected, lower HRTs presented higher reaction rates, the reaction rate is inversely proportional to the hydraulic retention time.
- Similar hydraulic retention times present different reaction rates, notably for the cluster WWTP CD 25 °C “b”, CD 1 and HLD 4 (Figure 24), and the cluster WWTP HLD 1 and HLD 3 (Figure 26).

The WWTPs with very high hydraulic retention times above 40 days present a high digester effectiveness. Longer reaction times will allow a more complete degradation of the total volatile solids. Even though the WWTPs with high HRTs (WWTP CD 3 to CD 7) presented an effective digestion performance, they did not present higher

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effectiveness than the standard design anaerobic digester from WWTP CD 2, nor than the digesters operated at low HRTs such as WWTP HLD 1 and HLD 4. The sludge composition, much more than the hydraulic retention time, influenced the digester effectiveness. Furthermore, once reaching maximum decomposition, no further degradation occurred, showing that extremely high hydraulic retention times do not improve digestion performance.

Decreasing hydraulic retention time combined with high total and organic solids concentration at the inflow resulted in increased digester efficiency, however efficiency did not improve homogeneously. Comparing WWTP HLD 4 and CD 1 with similar HRTs in the primary digester, the biogas production rate in WWTP HLD 4 is almost double the biogas production rate in WWTP CD 1. Various parameters influence this result:

- 1) The primary sludge quality for WWTP CD 1 should be better, considering the low fraction of organics in the PS of WWTP HLD 4.
- 2) The WAS quality of WWTP CD 1 should be worse than the one from WWTP HLD 4, considering higher sludge age. The organic loading rate of the digester of WWTP HLD 4 is estimated to be about 30 % higher than that of WWTP CD 1.

Contrary to the other WWTPs, the biogas production rate from WWTP CD 25 °C reduced with the decrease of the hydraulic retention time. The organic loading rates for operational condition “a” and “b”

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were practically identical, however the hydraulic retention time and solids concentration fed to digester under condition “b” were double the HRT and solids content fed to the digesters under operational condition “a”.

WWTP HLD 1 presented a particularly interesting case, given its three distinct operational conditions. The inflow TVS concentration was practically constant, however, under different HRT regimes. Operational condition “b” presented the best digester performance among the three, likely due to its higher primary sludge fraction. Condition “a” followed closely. The evaluation of condition “c” showed that 30 % of the organic load removal occurred in the second reactor. Here it seemed the first reactor was overloaded and the second reactor was able to compensate the overload. It is relevant to point out, that the performance of the second digester was not so obvious, when only evaluating the TVS removal fraction (Ch. 7.1), it was necessary to evaluate the reaction rate. This effect is likely due to the elimination of the uncertainty of the non-biodegradable TVS fraction.

8. EFFECT OF SINGLE RATE KINETICS ON ANAEROBIC DIGESTER DESIGN

Levenspiel (1999) argues the advantages and disadvantages of using simple empirical kinetic equations. *The strongest argument in favor of searching for the actual mechanism is that [...] extrapolation to new and more favorable operating condition is much more safely done.* On the other hand, if different mechanisms fit the data equally well, it must be accepted that the selected equation can only be considered a good fit, not one that represents reality. Thus, there is no reason not to use the simplest and easiest to handle equation with satisfactory fit.

Even though they are a simplification of a much more complex set of interactions, single rate models are often used for anaerobic digester design on WWTPs. The simplest kinetics are first order kinetics. The main mechanistic limitation of this approach is that it only considers the effect of substrate concentration on the reaction rate and does not describe the effect of biomass or enzyme activity on the anaerobic digestion system.

It is surprising that Michaelis-Menten type kinetics are not commonly used to describe the anaerobic digestion process, considering that enzymes and microorganisms have a significant role. This might perhaps be explained by the difficulty of distinguishing between active biomass and total volatile solids in the anaerobic digestion of sludge (TOMEI et al., 2009). This chapter presents the mass balance

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equations for first order kinetics and Michaelis-Menten type kinetics in CSTRs and discusses the effect of kinetics in single rate models for anaerobic digester design on WWTPs.

8.1. FUNDAMENTAL CONSIDERATIONS

The goal of the presented unstructured models is to identify relevant reaction basics and deduce sensible design recommendations, not to analyze the intricate details within the realm of anaerobic digestion. Next to the obvious simplification, that a single rate kinetic approach does not describe the production, consumption and accumulation of intermediate metabolites of the anaerobic digestion process, some further simplifications apply:

- The biomass yield from substrate is constant, thus biomass growth rate is directly proportional to substrate removal rate.
- Substrate concentration and substrate availability are considered identical.¹³
- Enzyme concentration is directly proportional to biomass concentration. Thus, the mathematical background of the Michaelis-Menten kinetics directly applies to bacterial or

¹³ It could occur that an increase in substrate concentration does not result in an increase of substrate availability. E.g., a linear polymer is added to the reactor and biomass can only degrade this polymer through one end. If a longer linear polymer is added, concentration will increase, but the degradation rate will not. This is not considered in the presented models.

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Monod kinetics. There is no differentiation between biomass or enzyme concentration. Thus, the kinetics are dubbed “Michaelis-Menten *type*” kinetics, focusing on the mechanistic principle.

- There are no specific inhibitions (pH, VFA, NH_3), alkalinity is sufficient in sludge from municipal WWTPs, no excess dissolved material or toxic substances fed to the system are expected. No significant ammonia overloads are expected.
- No biomass death rate is included.
- No biomass-maintenance-factor is included.
- The presented kinetic values like K_s and $k_{C_{\max}}$ are apparent values. They are classified as the macro kinetic aspect of reactor design and are subject to variation, among others due to the kinetics of transport to the reaction location.
- The refractory coefficient to account for the non-biodegradable portion of the organic substrates in the digester is constant. There is no increase due to biodegradation under steady state conditions.
- The fluid is non-segregated.
- Inflow and outflow is identical, loss due to the biogas flow is considered marginal.
- All considerations are for continuous stirred tank reactors. Sludge retention time and hydraulic retention time are identical.

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The set of equations used to describe the relation between biomass, substrate and biogas production in a CSTR for up to two tanks in series derives from the mass balance presented in Figure 27.

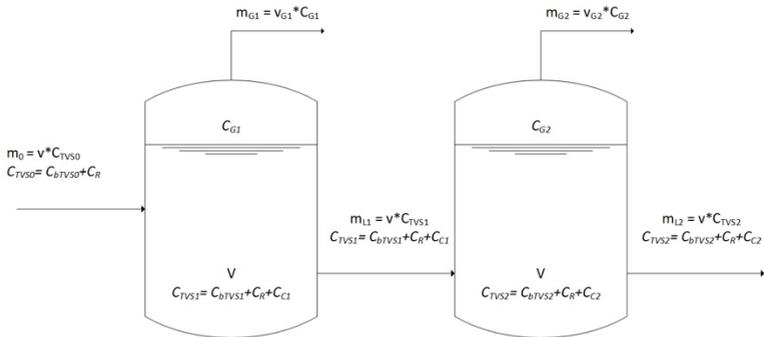


Figure 27: Fundamental CSTR mass balance for two anaerobic digesters of the same size set in series under steady state conditions.

The inflow organic mass (m_0) is the product of the flow (v) and the total volatile solids concentration (C_{TV50}) composed of biodegradable (C_{bTV50}) and recalcitrant fractions (C_R). The outflow mass of the liquid phase for the first reactor (m_{L1}) is the product of the flow (v) and the organic solids concentration in the reactor and outflow (C_{TV51}) composed of a biodegradable concentration (C_{bTV51}), a cell concentration (C_{C1}) and the same recalcitrant concentration of the input (C_R). The outflow mass of the gas phase (m_{G1}) is the product of the gas concentration (C_{G1}) and the respective gas flow (v_{G1}). The composition of the outflow mass of the second reactor (m_{L2}) is composed of the same elements as for the first reactor. The fundamental difference between the mass balances of the first and

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second reactor is that the second reactor has biomass (C_{C1}) at the inflow. Table 23 presents the general mass balance equations for one and two tanks in series.

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Table 23: General mass balance equations for one and two tanks in series for steady state conditions

Description	Equation	Units	
Yield biomass from substrate	$Y_{C/bTVS} = -\frac{r_C}{r_{bTVS}}$	[1]	Eq. 69
Yield biogas from substrate	$Y_{G/bTVS} = -\frac{r_G}{r_{bTVS}}$	[1]	Eq. 70
Biomass growth rate	$r_{Ci} = \frac{C_{Ci} - C_{C(i-1)}}{\tau} = Y_{C/bTVS} * r_{bTVSi}$	[kg/(m ³ *d)]	Eq. 71
Biogas production rate	$r_{Gi} = Y_{G/bTVS} * r_{bTVSi}$	[kg/(m ³ *d)]	Eq. 72
Biomass concentration reactor 1 (considering CSTR and C _{C0} = 0)	$C_{C1} = Y_{C/bTVS} * r_{bTVS1} * \tau$	[kg/m ³]	Eq. 73
Biomass concentration reactor 2 (considering CSTR and C _{in} = C _{C1})	$C_{C2} = Y_{C/bTVS} * r_{bTVS2} * \tau + C_{C1}$	[kg/m ³]	Eq. 74
Total volatile solids concentration at inflow	$C_{TVS0} = TVS0_M * \rho = C_{bTVS0} + C_R$	[kg/m ³]	Eq. 75
Total volatile solids concentration at outflow reactor 1 (CSTR)	$C_{TVS1} = TVS1_M * \rho = C_{bTVS1} + C_{C1} + C_R$	[kg/m ³]	Eq. 76
Total volatile solids concentration at outflow reactor 2 (CSTR)	$C_{TVS2} = TVS2_M * \rho = C_{bTVS2} + C_{C2} + C_R$	[kg/m ³]	Eq. 77
TVS stabilization fraction in reactor 1 (CSTR)	$U_{TVS1} = \frac{C_{bTVS0} - (C_{bTVS1} + C_{C1})}{C_{bTVS0} + C_R}$	[1]	Eq. 78
TVS stabilization fraction in reactor 2 (CSTR)	$U_{TVS2} = \frac{C_{bTVS1} - (C_{bTVS2} + C_{C2})}{C_{bTVS1} + C_{C1} + C_R}$	[1]	Eq. 79
TVS stabilization fraction of 2 tanks in series	$U_{TVS1S} = \frac{C_{bTVS0} - (C_{bTVS2} + C_{C1} + C_{C2})}{C_{bTVS1} + C_{C1} + C_R}$	[1]	Eq. 80

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Eq. 69 shows the ratio between the cell production and the biodegradable substrate consumption, or biomass yield ($Y_{C/bTVS}$). Eq. 70 shows the ratio between biogas production and substrate consumption, or biogas yield ($Y_{G/bTVS}$). From the basic mass balance for CSTR, Eq. 71 presents the biomass growth rate. Biogas production rate can be determined by rewriting Eq. 70 as Eq. 72. Eq. 73 and Eq. 74 present the biomass concentration in each reactor. Eq. 75, Eq. 76 and Eq. 77 characterize the composition of total volatile solids at the inflow to the first digester, the inflow to the second digester and the outflow of the second digester. Eq. 78, Eq. 79 and Eq. 80 describe the observed total volatile solids stabilization fraction in the first reactor, the second reactor and the combined volatile solids stabilization fraction.

8.2. DIGESTER DESIGN WITH SINGLE RATE FIRST ORDER KINETICS

The 1st order kinetic in a CSTR has the particular elegant feature that the mathematics are fairly straight forward allowing it to be a good first estimate on digester efficiency and performance.

8.2.1. DIGESTER DESIGN EQUATIONS

Considering the mass balance of Figure 27 and Table 23, the equations presented in Table 12 by DWA (2014) can be adapted and expanded as presented in

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Table 24. Biodegradable TVS concentration and biomass concentration in the reactor, as well as reactor performance parameters regarding TVS removal rate and TVS removal fraction were deduced

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Table 24: Model based approach for two same size CSTR reactors, adapted from DWA (2014)

Description	Equation	Units	
First order kinetic rate for biodeg. TVS removal	$r_{bTVS} = k_{Hyd} * C_{bTVS}$	[kg/(m ³ *d)]	Eq. 81
Biodeg. TVS conc. reactor 1 (CSTR)	$C_{bTVS1} = \frac{C_{bTVS0}}{1 + k_{Hyd} * \tau}$	[kg/m ³]	Eq. 82
Biodeg. TVS conc. reactor 2 (CSTR)	$C_{bTVS2} = \frac{C_{bTVS0}}{(1 + k_{Hyd} * \tau)^2}$	[kg/m ³]	Eq. 83
Biomass conc. in reactor 1 (CSTR)	$C_{C1} = Y_{C/bTVS} * \frac{C_{bTVS0} * k_{Hyd}}{1 + k_{Hyd} * \tau} * \tau$	[kg/m ³]	Eq. 84
Biomass conc. in reactor 2 (CSTR)	$C_{C2} = Y_{C/bTVS} * \frac{C_{bTVS0} * k_{Hyd}}{(1 + k_{Hyd} * \tau)^2} * \tau + C_{C1}$	[kg/m ³]	Eq. 85
TVS removal rate reactor 1 (CSTR)	$r_{bTVS1} = \frac{C_{bTVS0} * k_{Hyd}}{1 + k_{Hyd} * \tau}$	[kg/(m ³ *d)]	Eq. 86
TVS removal rate reactor 2 (CSTR)	$r_{bTVS2} = \frac{C_{bTVS0} * k_{Hyd}}{(1 + k_{Hyd} * \tau)^2}$	[kg/(m ³ *d)]	Eq. 87
Biogas production rate in reactor i (CSTR)	$r_{G1} = \frac{Y_{G/bTVS} * r_{bTVSi}}{\rho_G}$	[m ³ /(m ³ *d)]	Eq. 88
Biodegradable TVS stabilization fraction in reactor i (CSTR)	$U_{bTVSi} = \frac{\rho_G * \tau}{1 + k_H * \tau}$	[1]	Eq. 89
Total Biodeg. TVS stabilization in 2 reactors (CSTR - TiS)	$U_{bTVS1+2} = 1 - \left(\frac{1}{1 + k_{Hyd} * \tau} \right)^2$	[1]	Eq. 90
Observed TVS stabilization fraction in reactor 1 (CSTR)	$U_{TVS1} = \frac{k_{Hyd} * \tau}{1 + k_{Hyd} * \tau} * \frac{C_{bTVS0} * (1 - Y_{C/bTVS})}{C_{bTVS0} + C_R}$	[1]	Eq. 91
Biogas production in reactor 1 (CSTR)	$U_{G1} = \frac{Y_{G/bTVS} * (C_{bTVS0} - C_{bTVS1})}{\rho_G * C_{TVS0}}$	[m ³ /kgTVS]	Eq. 92
Biogas production in two reactors in series (CSTR)	$U_{G1+2} = \frac{Y_{G/bTVS} * (C_{bTVS0} - C_{bTVS2})}{\rho_G * C_{TVS0}}$	[m ³ /kgTVS]	Eq. 93

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Eq. 81 presents the fundamental kinetic relationship between reaction rate and biodegradable total volatile solids. Eq. 82 and Eq. 83 present the biodegradable TVS concentration in the first and second reactor in series, while Eq. 84 and Eq. 85 present the respective biomass concentrations. Eq. 86, Eq. 87 and Eq. 88 present the reaction rates for substrate removal and biogas production in the first and second reactors, while Eq. 89 and Eq. 90 present the biodegradable volatile solids stabilization fraction. Eq. 91 presents the total volatile solids stabilization fraction including the biomass and recalcitrant organic fractions. Eq. 91 characterizes the observed TVS removal fraction. Eq. 92 and Eq. 93 show the biogas production per added total volatile solids, typical of digester characterization.

A relevant compromise made when applying first order kinetics to biologic systems, is that the reaction rate will only be dependent on the substrate concentration (Eq. 81). Analyzing the equations for digester design, considering first order kinetics presented in

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Table 24, five relevant variables are observed, namely: the temperature “ T ”, which influences the hydrolysis constant “ k_{Hyd} ”, the inflow biodegradable total volatile solids concentration “ C_{bTVSO} ”, the hydraulic retention time “ τ_m ” and the recalcitrant fraction “ C_R ”.

A consequence from selecting first order kinetics for reactor design is that the substrate concentration in the first reactor (Eq. 82) and second reactor (Eq. 83) (and every consecutive reactor) will be directly proportional to the initial substrate concentration, kinetic constant and hydraulic retention time. The biomass concentration, as well as the substrate concentration, are functions of the inflow substrate and the resulting substrate to biomass ratio will be exclusively proportional to the hydraulic retention time and kinetic constant. Variation of substrate concentration will not influence the substrate to biomass ratio. This is a fundamental difference towards Michaelis-Menten type kinetics.

The exclusive dependency on the substrate inflow concentration under first order kinetics also has an effect on the TVS stabilization grade prediction, in a CSTR under steady state condition, the inflow concentration will be cancelled out resulting in Eq. 89. This implies that substrate concentration does not determine digester effectiveness. Only the HRT and the kinetic constant (and temperature) influence digester effectiveness. Thus, the only motivation to thicken the inflow sludge is the economic driver of reaching smaller digesters for the desired hydraulic retention time.

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Another consequence of first order kinetics is that it does not describe cell washout. The reaction rate is at its highest at the lowest hydraulic retention time. Digester effectiveness described by the substrate removal rate (Eq. 86) or the biogas production rate (Eq. 72) and is expressed as a function of the inflow of biodegradable substrate concentration " S_{B0} ", temperature " T " and the hydrolysis constant " k_{Hyd} ". In Eq. 86 when $\tau_m \rightarrow 0$ $r_{TVS1} \rightarrow C_{bTVS0} * k_{Hyd}$. Reality does not reflect this and typically, minimum hydraulic retention times apply when selecting this type of kinetics for anaerobic digester design.

8.2.2. INFLUENCE OF FIRST ORDER KINETICS ON THE IMPROVEMENT OF DIGESTER EFFECTIVENESS

The application of the first order kinetic scheme leads to the conclusion that there are four ways to improve digestion efficiency: increasing hydraulic retention time, increasing temperature, reducing the recalcitrant fraction or increasing the hydrolysis constant. The recommended temperature for mesophilic digesters varies between 35 °C and 40 °C. The recalcitrant fraction varies according to sludge quality. In the best-case scenario only primary sludge with a low recalcitrant fraction of about 30 % will be present, in the worst case scenario only WAS will be present with a recalcitrant fraction of about 55 % (DWA, 2014). Different values of the hydrolysis constant are presented in literature, varying from 0.2 1/d (PAVLOSTATHIS; GIRALDO-GOMEZ, 1991), to 1 1/d (ANGELIDAKI; ELLEGAARD; AHRING, 1999) to 10 1/d (BATSTONE et al., 2002 a/b).

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Table 25 presents the variations of digester design parameters from literature considering 1st order kinetics.

Table 25: Overview of typical first order kinetic design parameters

Parameter	Units	Min.	Med.	Max.	Bench mark
Temperature	[°C]	30	35	40	35
Recalcitrant Fraction	[%TVS _T s]	55 %	42.5 %	30 %	42.5 %
Biodegradability	[%TVS _T s]	45 %	57.5 %	70 %	57.5 %
k_{Hyd}	[1/d]	0.2	1	10	0.26

The sensitivity of the parameters presented in Table 25 is investigated and compared to the benchmark digestion design recommendations from DWA (2014). Figure 28 a) presents the benchmark digestion efficiency as percentage of removed volatile solids according to Eq. 91, assuming a reaction temperature of 35 °C, 57.5 % TVS biodegradability of the initial volatile solids concentration, a reaction rate of 0.26 1/d and a biomass substrate yield of 0.05. It shows the influence of the biomass concentration over the measured output. Under the same conditions, Figure 28 b) presents the influence of temperature in a range between 20 °C and 40 °C. Figure 28 c) presents the effect of the recalcitrant fraction, or TVS biodegradability. Here the maximum value considers exclusively primary sludge degradation with 70 % biodegradability, the medium value considers the benchmark digester with 57.5 % biodegradability and the minimum value considers exclusively waste activated sludge with 45 % biodegradability. Figure 28 d) presents the effect of the

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applied hydrolysis constant varying from 0.2 1/d, to 1 1/d to 10 1/d as in literature.

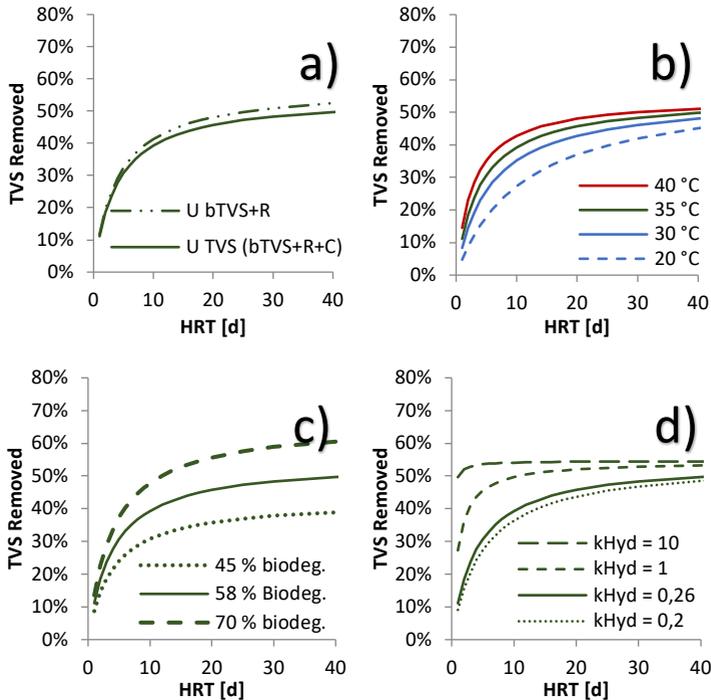


Figure 28: Simulated TVS stabilization fraction for 1st order kinetics in reactor 1 (CSTR) considering benchmark data and its variations (Table 25). a) effect of biomass, b) effect of temperature, c) effect of biodegradability, d) effect of hydrolysis constant

Figure 28 a) presents typical design conditions as described by DWA (2014) considering an even mix of primary and waste activated sludge. To reach an 85 % digestion efficiency (50 % TVS removal) about 20 days of HRT need to be selected. If biomass production in the digester is included in the anaerobic digester evaluation, the

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expected total volatile solids degradation fraction will be slightly lower.

Figure 28 b) shows that an increase in temperature will increase digestion efficiency. At 40 °C operational temperature the necessary HRT for 85 % digestion efficiency will be at about 15 days, while for 35 °C it will be at 20 days, at 30 °C it will reach 30 days and for 20 °C it gets up to 65 days of HRT. Thus, the size of the reactor will be significantly dependent on the capacity of controlling digester temperature.

Figure 28 c) shows that the type of sludge added to the digester will significantly affect the observed digestion efficiency, however, considering the parameter 85 % removal of the biodegradable substrate (59 % for PS and 38 % for WAS), the necessary HRT in both cases will be 20 days. In this case, the kinetic constant is identical for two different types of sludge. This does not necessarily apply to reality, and primary sludge can have a larger kinetic constant than waste activated sludge. What this analysis shows, is that when the biodegradability of the sludge fed to the digester is increased, biogas production might be higher and solids removal can be improved, however digester efficacy will not actually change, it will remain with 85 % removal of the biodegradable fraction at 20 days HRT.

Figure 28 d) shows the effect of the hydrolysis constant. A hydrolysis constant of 10 1/d would signify that a HRT of 1 day would already be sufficient to reach over 90 % of digestion efficiency. A hydrolysis

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constant of 1 1/d would signify that a HRT of about 6 days would allow 85 % of digestion efficiency. A hydrolysis constant of 0.2 1/d would signify that a HRT of about 25 to 30 days would be necessary to reach the recommended 85 % of digestion efficiency. Influencing the hydrolysis constant is thus an essential tool to improve digester efficiency.

The analysis of the curves in Figure 28 shows, that the selected hydrolysis constant and operational temperature influence the design of anaerobic digesters with first order kinetics. These parameters will have the most significant impact on the selected hydraulic retention time. It is also possible to observe that the most variations of digester efficacy occur below 20 days of hydraulic retention time. I. e., the variation of digester efficacy at 10 days HRT and 20 days HRT is significantly higher than from 20 to 30 or to 40 days.

A further digestion improvement can be achieved through consecutive digesters, or tanks in series. The solids removal can be determined for each digester according to Eq. 78 and Eq. 79, and the combined TVS removal can be determined according to Eq. 80. Considering the conditions of the benchmark anaerobic digester, 85 % TVS removal will be reached at 20 days HRT for one digester, however two digesters of 10 days HRT in series will reach 94 % TVS removal. (HEINDL; ROEDIGER, 2016).

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Increase of hydraulic retention time, increase in temperature, improvement of the kinetic parameters and multiple reactors systems are methods of choice to improve digester effectiveness.

This kinetic approach suggests the following strategies:

- Increase solids concentration to the digester. Consequences are reduced inflow, increased HRT and improved heat management;
- Treatment of the incoming sludge, e.g. through thermal hydrolysis, aiming at improving the hydrolysis constant and biodegradability; and
- Set digesters in series to improve efficiency.

8.2.3. INFLUENCE OF FIRST ORDER KINETICS ON THE IMPROVEMENT OF DIGESTER EFFICIENCY

Digester performance can be evaluated through the reaction rate with which solids are decomposed or biogas is produced. The reaction rate is independent of the recalcitrant fraction. Eq. 86 shows that the following parameters influence the reaction rate for first order kinetics: inflow of biodegradable substrate concentration " C_{bTVS0} ", the temperature " T " and the hydrolysis constant " k_{Hyd} ". FIGURE 29 a) shows the substrate removal rate for first order kinetics considering a common range of initial TVS concentration of 20 g_{TVS}/l, 30 g_{TVS}/l and 40 g_{TVS}/l. Figure 29 b) shows the substrate removal rate for first order kinetics considering reactor temperatures varying between 20 °C and 40 °C. Figure 29 c) shows the reaction rate

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considering biodegradability fractions of 45 %, 57.5 % and 70 % of C_{TVS0} . Figure 29 d) shows the substrate removal rate considering the variation of the hydrolysis constant.

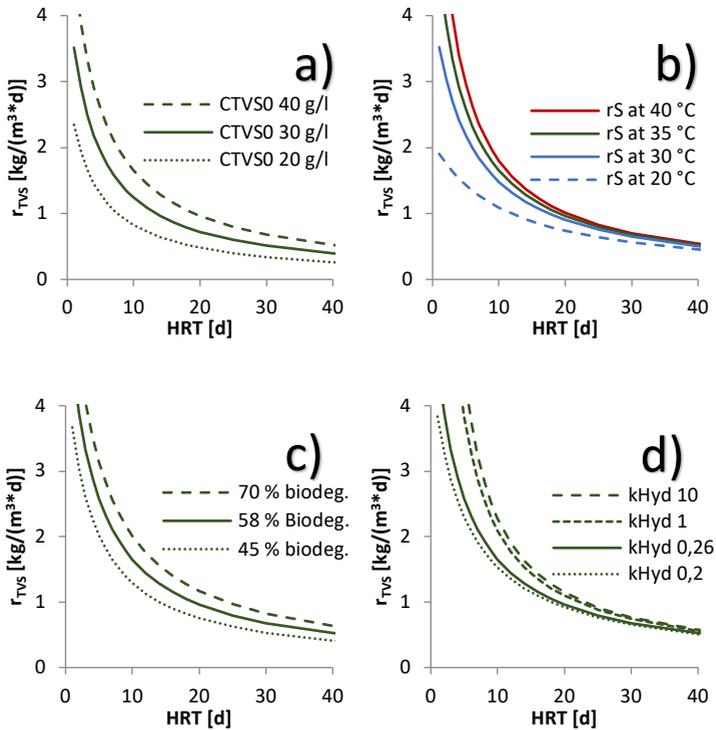


Figure 29: Simulated TVS removal rates for 1st order kinetics in reactor 1 (CSTR) considering benchmark data and its variations (Table 25). a) effect of substrate concentration, b) effect of temperature, c) effect of biodegradability, d) effect of hydrolysis constant

In Figure 29 a), it is possible to observe that the inflow concentration of biodegradable substrate has a significant effect on the TVS removal rate. Doubling the inflow concentration will double the

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reaction rate. Figure 29 b) shows that at higher temperatures the reaction rate will be slightly higher. At 20 days HRT for 30 °C to 40 °C the solids removal rate increases from 0.9 kg_{TVS}/(m³*d) to 1.1 kg_{TVS}/(m³*d) for an inflow concentration of 40 g_{TVS}/l. At lower HRTs, the influence of temperature increases. Increased biodegradability produces a similar effect to higher initial substrate concentrations. Figure 29 c) shows the same effect as observed in Figure 29 a). Higher substrate availability will result in higher reaction rates. Figure 29 d) shows that if it is possible to increase the low hydrolysis constant of 0.2 1/d to 1.0 1/d at 20 days HRT an improvement in the TVS removal rate will be obtained, however further increase of the hydrolysis constant will not have significant effect on the reaction rate. Improving the hydrolysis constant from 1 1/d to 10 1/d does not improve the reaction rate significantly at a HRT of 20 days. The reactor efficiency will be similar at hydraulic retention times above 20 days, irrespective of the hydrolysis constant. At lower hydraulic retention times, the hydrolysis constant has a significant influence. Thus, only at lower hydraulic retention times it is interesting to influence the hydrolysis constant.

Analyzing the behavior of the digester performance curves it is possible to show that the TVS removal rate is significantly affected by substrate availability (Figure 29 a) and c)), as expected for first order kinetics. Decrease of hydraulic retention times and higher initial substrate concentrations will improve digester efficiency. At lower

HRTs, higher temperatures and improvement of the kinetic parameters will also positively impact digester efficiency.

8.3. DIGESTER DESIGN WITH SINGLE RATE MICHAELIS-MENTEN TYPE KINETICS

This chapter will focus on the effect of Michaelis-Menten type kinetics, proposing that enzymatically catalyzed biochemical reactions and enzyme producing biomass concentration fundamentally rule the anaerobic digestion of wastewater sludge. The possibilities and limitations of the kinetic approach will be identified. From a mechanistic point of view, Michaelis-Menten type kinetics have the advantage of describing two important characteristics of the biologic reaction: the effect of substrate and the effect of the catalyzer be it the enzyme or biomass, over the biologic process.

8.3.1. DIGESTER DESIGN EQUATIONS

Considering the mass balance of Figure 27 and Table 23, the equations presented in chapter 4.1.3, chapter 4.1.4 and chapter 4.1.6 can be adapted and expanded to the anaerobic digestion process as presented in Table 26. Biodegradable TVS concentration " C_{bTVS} " and biomass concentration " C_C " in the reactor, as well as reactor performance parameters regarding TVS removal rate and TVS removal fraction, biogas production per added biodegradable volatile solids and biogas production rate per reactor volume were deduced. Table 26 presents the set of equations that describe a CSTR

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ruled by Michaelis-Menten type kinetics adapted to an anaerobic digester receiving biodegradable and recalcitrant substrate.

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Table 26: Michaelis-Menten type based model for CSTR digestion design

Description	Equation	Unit	
Specific biomass growth rate	$k_C = k_{Cmax} * \frac{C_{bTVS}}{C_M + C_{bTVS}}$	[1/d]	Eq. 94
Specific biomass growth rate ($C_M \gg C_{bTVS}$ pseudo 1 st Order)	$k_{C1st} = k_{Cmax} * \frac{C_{bTVS}}{C_M}$	[1/d]	Eq. 95
Specific biomass growth rate ($C_{bTVS} \gg C_M$ pseudo 0 th Order)	$k_{C0th} = k_{Cmax}$	[1/d]	Eq. 96
Biomass growth rate	$r_C = k_C * C_C$	[kg/(m ³ *d)]	Eq. 97
Yield of Enzyme from Biomass	$Y_{E/C} = \frac{r_E}{r_C}$	[1]	Eq. 98
Enzyme production rate	$r_E = Y_{E/C} * k_C * C_C = k_E * C_C$	[kg/(m ³ *d)]	Eq. 99
Specific biomass growth rate reactor 1 (CSTR and considering $C_{co} = 0$)	$k_C = \frac{1}{\tau}$	[1/d]	Eq. 100
Biodegradable TVS concentration reactor 1 (CSTR)	$C_{bTVS} = \frac{C_M}{\tau * k_{Cmax} - 1}$	[kg/m ³]	Eq. 101
Biodegradable TVS removal rate reactor 1 (CSTR)	$r_{TVS1} = \frac{C_{bTVS0} - C_{bTVS1}}{\tau} = \frac{C_{bTVS0} - \frac{C_M}{\tau * k_{Cmax} - 1}}{\tau}$	[kg/(m ³ *d)]	Eq. 102
Biogas production rate in reactor 1 (CSTR)	$r_{G1} = \frac{Y_{G/bTVS} * r_{bTVS1}}{\rho_G}$	[m ³ /(m ³ *d)]	Eq. 103
Biomass concentration reactor 1 (considering CSTR and $C_{co} = 0$)	$C_{C1} = Y_{C/bTVS} * r_{bTVS1} * \tau$	[kg/m ³]	Eq. 104
Biodegradable TVS stabilization fraction in reactor i (CSTR)	$U_{bTVSi} = 1 - \frac{C_M}{C_{bTVS(i-1)} * (\tau * k_{Cmax} - 1)}$	[1]	Eq. 105
TVS stabilization fraction in reactor 1 (CSTR)	$U_{TVS1} = \left(C_{bTVS0} - \frac{C_M}{\tau * k_{Cmax} - 1} \right) * \frac{(1 - Y_{C/bTVS})}{C_{bTVS0} + C_R}$	[1]	Eq. 106
Biogas production in reactor 1 (CSTR)	$U_{G1} = \frac{Y_{G/bTVS} * (C_{bTVS0} - C_{bTVS})}{\rho_G * C_{TVS0}}$	[m ³ /kg _{TVS}]	Eq. 107
Biogas production in two reactors in series (CSTR)	$U_{G1+2} = \frac{Y_{G/bTVS} * (C_{bTVS0} - C_{bTVS2})}{\rho_G * C_{TVS0}}$	[m ³ /kg _{TVS}]	Eq. 108

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The specific biomass growth rate " k_c " determines the biomass growth according to substrate concentration " C_{bTVS} " and the kinetic constants maximum biomass growth rate " k_{cmax} " and Michaelis-Menten type constant " C_M " (Eq. 94). The extreme conditions of the Michaelis-Menten kinetics, namely the "pseudo first order reaction" where $C_M \gg C_{bTVS}$ (Eq. 95) and "pseudo 0th order reaction where $C_{bTVS} \gg C_M$ (Eq. 96) are presented. The "pseudo first order reaction" is of interest to understand the often described first order kinetics. Observed first order kinetics are arguably an extreme condition from the Michaelis-Menten kinetics. The biomass growth rate " r_c " is directly proportional to the biomass concentration " C_C " (Eq. 97). It is assumed that biomass and exo-enzyme " C_E " concentrations and their production rates " r_c " and " r_E " are directly proportional (Eq. 98 and Eq. 99). In the first CSTR reactor, the specific biomass growth rate is inversely proportional to the hydraulic retention time " τ_m " (Eq. 100). The biodegradable substrate concentration in the reactor " C_{bTVS} " (Eq. 101) originates from Eq. 94 and Eq. 100. Eq. 102 presents the biodegradable substrate degradation rate. Eq. 103 presents the biogas production rate. The biomass concentration in the reactor is derived from Eq. 69 and can be expressed through Eq. 104, assuming no biomass concentration at the inflow. Eq. 105, Eq. 106, Eq. 107 and Eq. 108 respectively express the biodegradable stabilization fraction, the total volatile solids stabilization fraction, the biogas production per total volatile solids added and the biogas production of two reactors in series.

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For two reactors in series ruled by Michaelis-Menten type kinetics, biomass from the primary tank feeds to the secondary tank and the mass balance has to be adapted to consider inflow biomass C_{C1} . For Michaelis-Menten type kinetics considering inflow of biomass to the CSTR Levenspiel (1999) described the mass balance according to Eq. 24. The values for biomass production, product formation, reaction rate and biodegradability for a second CSTR digester ruled by Monod kinetics base on Eq. 24 and the equations presented in Table 23.

Analyzing the equations for digester design considering Michaelis-Menten type kinetics it is possible to observe five relevant variables: the Michaelis-Menten type constant C_M , the maximum specific biomass growth rate k_{Cmax} , the inflow biodegradable substrate concentration " C_{bTVS0} ", the hydraulic retention time " τ_m " and the recalcitrant fraction " S_R ".

By applying Michaelis-Menten type kinetics in a CSTR in steady state, the biodegradable substrate concentration " C_{bTVS} " will be a function of the hydraulic retention time " τ_m " and the kinetic parameters " k_{Cmax} " and " C_M ". This means that irrespective of the substrate inflow concentration, for a specific hydraulic retention time and kinetic parameters, the biodegradable substrate concentration will be the same. This occurs through the influence of the substrate concentration over the biomass concentration. A decrease in the hydraulic retention time will result in an increase of the substrate concentration in the reactor and consequently increase the specific

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biomass growth rate " k_c ", resulting in an increase of the biomass growth rate " r_c ", which ultimately will influence the biomass concentration " C_c ". The biomass concentration will be proportional to the difference between the biodegradable substrate concentration at the inflow and the substrate concentration at the specific HRT of operation. Thus, the substrate biomass ratio will be variable according to the HRT and the inflow substrate concentration. An increase in initial substrate concentration will result in an increase of biomass concentration in the reactor. For the purpose of this thesis, the effect of initial substrate concentration on the biomass concentration is the most significant difference between first order kinetics and Michaelis-Menten type kinetics. When Michaelis-Menten type kinetics apply, increasing substrate concentration at the inflow increases substrate removal.

Another consequence of Michaelis-Menten type kinetics is that it describes cell washout. Eq. 102 expresses digester effectiveness, or reaction rate. The reaction rate increases with reducing hydraulic retention times as " $\tau_m * k_{C_{max}} - 1 > 1$ ". Once " $0 < \tau_m * k_{C_{max}} - 1 < 1$ ", reaction rate decreases again until it reaches the undefined point where $\tau_m * k_{C_{max}} = 1$. This allows the designer to take into account the minimum necessary digester size as well as the optimal reaction rate.

8.3.2. BOUNDARY CONDITIONS FOR THE USE OF MICHAELIS-MENTEN TYPE KINETICS

Michaelis-Menten kinetics only arise under the specific condition known as the standard Quasi Steady State Assumption (sQSSA), where the sum of substrate concentration and the kinetic constant C_M is significantly higher than the catalyzer concentration (SEGEL; SLEMROD, 1989). Under different boundary conditions, the ODE system will have a different solution. Schnell and Maini (2000) argue that when the enzyme concentration is significantly higher than the sum of substrate concentration and reaction constant C_M , the condition for Michaelis-Menten kinetics is no longer valid, and the solution of the differential equation system will result in first order kinetic equations. This condition would arise mainly in systems with very low C_M values or at very low substrate concentrations. This assumption is the rQSSA, where the initial assumption for process design is that enzyme concentration is significantly higher than substrate concentration. Sanders et al. (2000) suggest such an approach for the modelling of a UASB reactor. This approach is reasonable for systems that separate sludge age and hydraulic retention time, such as the case of UASB reactor.

An extreme case of the Michaelis-Menten type kinetics where substrate concentration is particularly low, results in "pseudo first order kinetics". When assuming this condition, the sQSSA condition of $C_A + C_M \gg C_E$ still has to be satisfied. This would be accurate if the substrate concentration is low and the C_M has a relatively high value

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compared to the enzyme or biomass concentration. This implies that within the Michaelis-Menten canonical enzymatic equation (Eq. 9) the catalysis constant (k_2) and/or the dissociation constant (k_{-1}) of the substrate-enzyme complex are relatively high with regard to the formation constant (k_1). In this case, the specific biomass growth rate for pseudo 1st order kinetic for a CSTR with no biomass inflow can be determined as presented in Eq. 95.

Typical values for the inflow total volatile solids to anaerobic digesters vary between 20 g/l and 40 g/l. Assuming the benchmark biodegradable fractions 45 % and 70 % for WAS and PS respectively, the total biodegradable substrate concentration fed to the digester varies between 9 g/l and 28 g/l. If 85 % of the solids degrade within the digester, the biodegradable solids concentration would range from 1 g/l to 5 g/l. Given Eq. 104 and the typical yield value of anaerobic microorganisms of 0.05 (Table 27), the biomass fraction represents only 5 % of the removed substrate concentration and ranges between 0.4 g/l and 1.2 g/l. C_M values ranging between 1 g/l and 10 g/l were selected aiming to reach the observed values for “pseudo 1st order kinetics” observed in literature and discussed below. Under these conditions, the sQSSA condition to apply Michaelis-Menten are satisfied. Values between 0.12 1/d to 0.60 1/d were selected for k_{Cmax} . The benchmark WWTP was defined as having inflow volatile solids concentration of 30 g/l, 57.5 % biodegradable fraction, C_M at 5 g/l and k_{Cmax} at 0.36.

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Table 27: Overview of proposed Michaelis-Menten type kinetic design parameters

Parameter	Units	Min.	Med.	Max.
C_{TVS0}	[g/l]	20	30	40
Recalcitrant Fraction	[%TVS _{TS}]	30 %	42,5 %	55 %
Biodegradability	[%TVS _{TS}]	45 %	57,5 %	70 %
C_M	[g/l]	1	5	10
k_{Cmax}	[1/d]	0.12	0.36	0.60
Y_{c/bTVS}	[1]	0.05	0.05	0.05

Figure 30 shows the plot of the biodegradable substrate concentration as a function of k_c . The full line shows the biomass growth rate for an inflow concentration of 30 g/l of biodegradable solids, while the dashed line shows the same for a TVS0 concentration of 40 g/l and the dotted line for 20 g/l. The straight full line shows the pseudo first order kinetic. Considering that in a CSTR the biomass growth rate (k_c) is the inverse of the hydraulic retention time, the biomass growth rate would be identical to the pseudo 1st order constant if k_c was smaller than 0.05 1/d, which is equivalent to a hydraulic retention time larger than 20 days. In principle, when applying these parameters, all the anaerobic digesters built as CSTRs with a hydraulic retention time of more than 20 days could be described through pseudo 1st order kinetics. At low substrate concentrations, the biomass production rate will be low and directly proportional to substrate concentration, resulting in a pseudo first

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order kinetic reaction rate. At higher substrate concentration, the Michaelis-Menten type kinetics will become apparent.

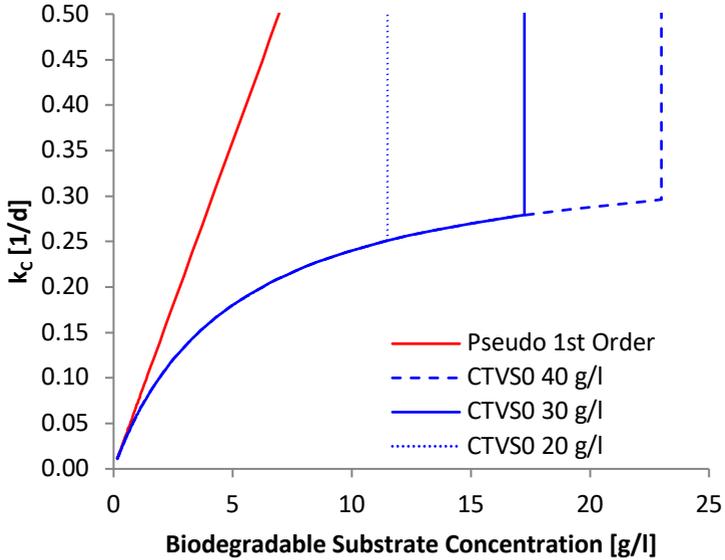


Figure 30: Michaelis-Menten type kinetics for biodegradable substrate concentration considering $C_M = 5$ g/l and $k_{Cmax} = 0.360$ 1/d

8.3.3. INFLUENCE OF MICHAELIS-MENTEN TYPE KINETICS ON DIGESTION EFFICIENCY

The application of Michaelis-Menten type kinetic scheme leads to the conclusion that there are four ways to improve digestion efficiency: increase the hydraulic retention time, increase the inflow substrate concentration C_{bTVS0} (or reduce the recalcitrant fraction), increase the specific biomass growth rate " k_c " or decrease the Michaelis-Menten type kinetic constant " C_M ". Constant temperature values of 35 °C in the reactor are assumed. No explicit effect of temperature is investigated, however it is reflected on the values of k_{Cmax} and C_M . Table 27 presents the input values.

Figure 31 a) presents the effect of the inflow substrate concentration " C_{bTVS0} " on the digester efficiency, assuming reaction temperature of 35 °C, 57.5 % TVS biodegradability of the initial volatile solids concentration, specific biomass growth rates of 0.36 1/d, C_M of 5 g/l and a biomass substrate yield of 0.05. It shows the effect of substrate concentration at the inflow. Under the same conditions, Figure 31 b) presents the effect of the recalcitrant fraction, or TVS biodegradability. Figure 31 c) shows the influence of the Michaelis-Menten type kinetic constant. Figure 31 d) presents the effect of the specific biomass growth rates " k_{Cmax} ".

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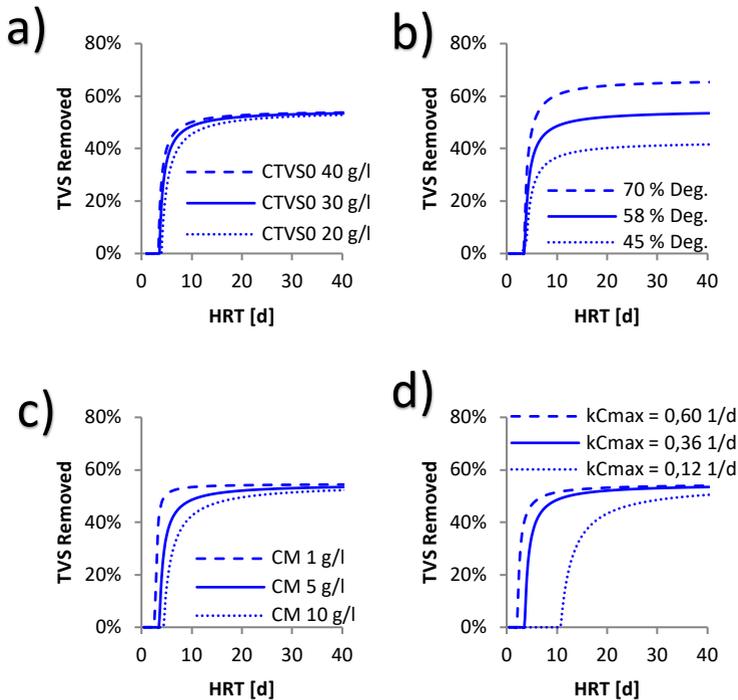


Figure 31: Simulated TVS stabilization fraction for Michaelis-Menten type kinetics in reactor 1 (CSTR) considering benchmark data and its variations (Table 27) a) effect of substrate concentration, b) effect of biodegradability, c) effect of Michaelis-Menten type constant " C_m ", d) effect of maximum specific growth rate " k_{Cmax} "

Even though the biodegradability of the total volatile solids in Figure 31 a) is 57.5 %, the apparent maximum TVS removal will lie at a slightly lower fraction of about 54 %. This occurs due to the influence of biomass concentration. The substrate degrades, however, it partially transforms into biomass, a parameter also measured in the total solids and total volatile solids analysis. Even though the biomass

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concentration is relatively small, it has an effect of the apparent total volatile solids removal.

In Figure 31 a), it is possible to observe that the increase in substrate concentration in the feed will result in a slight improvement of the solids stabilization fraction at lower HRTs. At 20 days HRT, the TVS removal improves from 51 % to 53 % when TVS concentration at the inflow increases from 20 to 40 g/l. At 10 days HRT, TVS removal improves from 45 % to 50 % when the TVS concentration at the inflow is increased. Thus, a reactor with 10 days HRT and 40 g/l TVS at the inflow will present practically the same performance as a reactor with 20 days HRT and 20 g/l TVS at the inflow. The 85 % TVS removal will be reached at 11 days for the digester with 20 g TVS/l at the inflow and 6.8 days for the digester with 40 g/l at the inflow.

Figure 31 b) shows the effect of the biodegradable fraction of the sludge fed to the digester. Similar to the conditions presented for first order kinetics, the TVS removal improves significantly with the increase of the biodegradable fraction. The improvement of the biodegradability however increases the degradable solids fraction and under Michaelis-Menten type kinetic systems, unlike the first order kinetics, this will result in an improvement of digester efficacy. Here the digester with 45 % biodegradable fraction requires 9.5 days to reach the benchmark 85 % degradation fraction, while the digester with 57.5 % degradable fraction needs 8 days and the one with 70 % degradable fraction only needs 7.3 days to reach that benchmark.

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Figure 31 c) presents the effect of the half rate constant C_M . The selected values are significantly higher than the ones registered in literature for individual microorganisms. The argument is simple: the range is relevant for the problem, considering that combined substrate concentrations in the range of several grams are applied. The system with the C_M of 10 reaches the 85 % removal fraction at 13.5 days, while the system with the C_M of 1 g/l reaches 85 % TVS removal in less than 4 days. At 20 days HRT, the system with the C_M of 1 g/l reaches 99 % substrate removal efficiency, while the system with the C_M of 10 g/l reaches 91 % efficiency. Both cases reach the benchmark. The C_M parameter within the range from 1 g/l to 10 g/l is thus more relevant at lower hydraulic retention times.

The maximum specific biomass growth rate has a relevant effect on the digester effectiveness, as presented in Figure 31 d). Low maximum biomass growth rates result in a demand of longer hydraulic retention times to reach the same result. To reach the 85 % benchmark TVS removal the system with the $k_{C_{max}}$ value of 0.12 1/d needs 24 days, while the system with $k_{C_{max}}$ values of 0.60 1/d only needs 5 days. The washout point will be at 2 days HRT for $k_{C_{max}}$ 0.60 1/d, while it can increase to over 10 days HRT if $k_{C_{max}}$ decreases to 0.12 1/d. Variation of $k_{C_{max}}$ can occur due to non-competitive inhibition such as decrease in pH and increase in NH_3 concentration (BATSTONE et al., 2002a).

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Similar to first order kinetics, further digestion improvement can be achieved through consecutive digesters, or tanks in series. However, each individual digester has to be large enough to avoid washout. The TVS stabilization fraction can be determined for each digester according to Eq. 78 and Eq. 79, and the combined TVS stabilization fraction can be determined according to Eq. 80. Considering an inflow concentration of 30 g/l, a biodegradable fraction of 57.5 %, a C_M value of 5 g/l and a k_{Cmax} value of 0.36 1/d, 85 % TVS removal will be reached at 8 days HRT for the first digester. However, two digesters of 8 days HRT in series, totaling 16 days of combined hydraulic retention time will reach 99 % TVS removal. Given the risk of cell washout, very low HRTs are not recommended. Under the described conditions, at about 4 days of HRT cell washout occurs. If two digesters of 4 days are set in series, no TVS removal occurs. Due to cell washout, there will be no cell growth in the first reactor. Consequently, there is no cell feed to the second reactor and no cell growth in the second reactor. Thus, even though combined the hydraulic retention time is the same as for a digester with 85 % removal efficiency there is no substrate degradation. The advantage of Michaelis-Menten type kinetics over first order kinetics in this case, is that the former will predict this behavior, while the latter will not.

In principle, this kinetic approach will result in similar improvement measures as compared to first order kinetics. One notable difference is that the benchmark 85 % TVS removal is usually reached faster

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under the evaluated conditions. Considering Michaelis-Menten type kinetics, digester efficiency can be improved by the following strategies:

- increasing hydraulic retention time in the digester, increasing substrate concentration at the inflow, e. g. through improved thickening processes,
- increasing the biodegradable fraction, e.g. through thermal hydrolysis,
- improving the kinetic constants, by reducing the C_M value and increasing the $k_{C_{max}}$ value and
- setting multiple digesters in series, with the limitation of washout conditions.

While sludge biodegradability presented the most interesting property to work on, to increase substrate removal, under the evaluated parameters $k_{C_{max}}$ seemed to have the most significant influence on digester failure. From these observations, it would be relevant to inform operational staff responsible for digester operation to control non-competitive inhibition such as ammonia shocks and high pH variations. Design engineers could contribute by preparing measures right from the concept phase to handle these potential situations.

8.3.4. INFLUENCE OF MICHAELIS-MENTEN TYPE KINETICS ON DIGESTER EFFICIENCY

Digester performance is evaluated through the reaction rate with which solids are decomposed or biogas is produced. The observed reaction rate is independent of the recalcitrant fraction. Eq. 102 shows the substrate removal rate for Michaelis-Menten kinetics. The parameters inflow of biodegradable substrate concentration " C_{bTVS0} " and the kinetic constants " C_M " and " $k_{C_{max}}$ " influence the reaction rate. Figure 32 a) shows the effect of substrate concentration on the reaction rate. Figure 32 b) shows the reaction rate considering biodegradability fractions of 45 %, 57.5 % and 70 % of C_{TVS0} . Figure 32 c) shows the effect of the C_M variation and Figure 32 d) the effect of $k_{C_{max}}$ variation.

Effect of Single Rate Kinetics on Anaerobic Digester Design

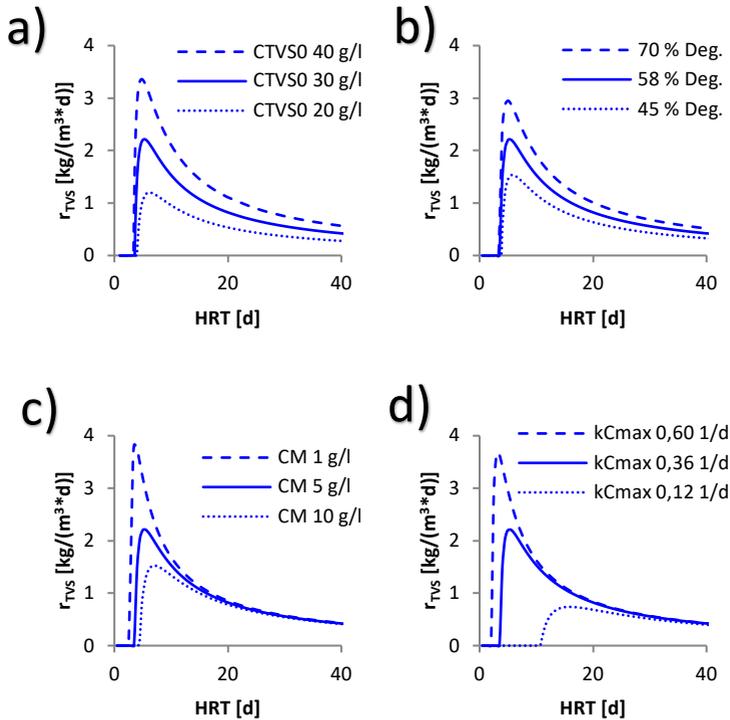


Figure 32: Simulated TVS removal rates for Michaelis-Menten type kinetics in reactor 1 (CSTR) considering benchmark data and its variations (Table 27) a) effect of substrate concentration, b) effect of biodegradability, c) effect of Michaelis-Menten type constant " C_M ", d) effect of maximum specific growth rate " k_{Cmax} "

Figure 32 a) and Figure 32 b) show that an increase in the TVS concentration at the inflow results in a directly proportional improvement of the overall reaction rate, similar as for the first order kinetics. The moment of washout decreases slightly as inflow substrate concentration is increased.

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Figure 32 c) shows the effect of the half concentration constant C_M . This constant is usually associated with competitive inhibition. A decrease of the C_M will result in a faster reaction rate. Under the analyzed conditions, this only has little effect at HRTs above 20 days. Even at 10 days HRT the increase in the reaction rate is small, varying from $1.3 \text{ kg}/(\text{m}^3 \cdot \text{d})$ to $1.5 \text{ kg}/(\text{m}^3 \cdot \text{d})$.

Figure 32 d) presents the effect of the specific biomass growth rate. This constant is usually associated with non-competitive inhibition. Here it is possible to observe that small growth rates have a significant effect on digester performance largely affecting the reaction rate and the point of washout. Controlling the non-competitive inhibition seems to be a sensible step in improving digester efficiency.

Overall the reaction rate for the Michaelis-Menten type kinetics shows a minimum hydraulic retention time, below which washout occurs. The reaction rate increases steeply until it reaches a maximum point and then decreases gradually until it reaches an asymptote. The washout occurs when $C_{bTVS0} - C_M / (\tau_m * k_{Cmax} - 1) \leq 0$ (Eq. 109). Thus, the range where $\tau_m * k_{Cmax} - 1 \leq C_M / C_{bTVS0}$ is outside the physical significance of the equation. The hydraulic retention time of the maximum reaction rate can be determined by equalizing the derivative over the hydraulic retention time of Eq. 102 to "0". This will result in Eq. 110.

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Washout (CSTR) Eq. 109

$$\tau * k_{Cmax} = \frac{C_M}{C_{bTVS0}} + 1$$

Hydraulic retention time at max. r_s (CSTR) Eq. 110

$$\tau = \frac{\sqrt{(C_{bTVS0} + C_M) + C_M * (C_{bTVS0} + C_M)}}{C_{bTVS0} * k_{Cmax}}$$

Substrate availability significantly affects the TVS removal rate. Decrease of hydraulic retention times and higher initial substrate concentrations will improve digester efficiency, up until a maximum. After this, reaction rate decreases significantly with shortening HRT finally resulting in a washout. It is possible to observe that most relevant effects of the kinetic constants occur below 20 days of hydraulic retention time.

For the same feed concentration, the treatment efficacy increases with hydraulic retention time, while treatment efficiency reduces gradually and eventually reaches an asymptote. The reactor specific mass reduction reaches a maximum where the proportion C_{bTVS}/τ is at its maximum, resulting in the highest availability of substrate for the microorganisms. The ideal hydraulic retention time will be dependent on the advantages of reducing substrate against the advantages of increasing specific reactor efficiency.

8.4. DESIGN OVERLAP

Michaelis-Menten type kinetics tend to first order kinetics under very low k_{Cmax} values (Figure 30), that in a CSTR are associated with high HRT values. Figure 33 and Figure 34 show the rate plots for digester

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efficacy and digester efficiency for the established benchmark WWTPs (Table 25 and Table 27).

At higher hydraulic retention times, first order kinetics and Michaelis-Menten type kinetics are interchangeable. At lower HRTs, this is no longer the case. In this case, if Michaelis-Menten type kinetics apply, using first order kinetics would result in an under estimation of the solids removal fraction for hydraulic retention times between 6 and 20 days. It would also not take into account the washout phenomena and result in an under estimation of the reaction rate for hydraulic retention times between 4 days and 20 days, and an over estimation of the reaction rate for hydraulic retention times below 4 days.

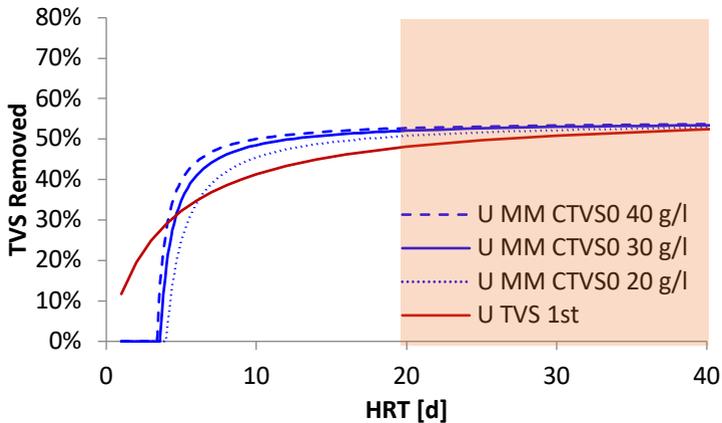


Figure 33: Digester design overlap for total volatile solids removed at benchmark parameters from Table 25 and Table 27. Red area indicates design overlap

Effect of Single Rate Kinetics on Anaerobic Digester Design

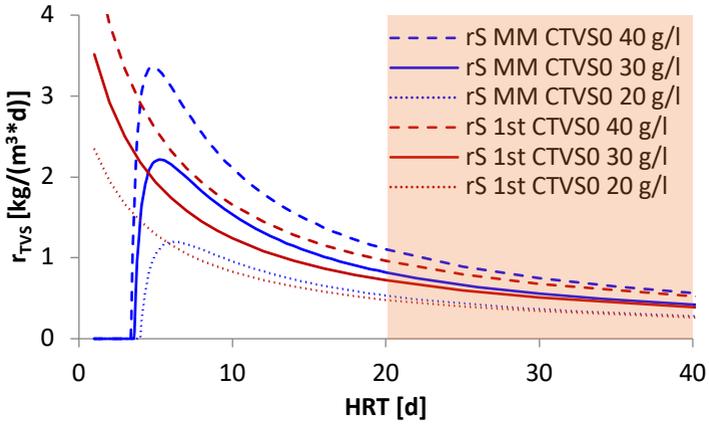


Figure 34: Digester design overlap for substrate removal reaction rate at benchmark parameters from Table 25 and Table 27. Red area indicates design overlap

9. FULL SCALE ANAEROBIC DIGESTER PERFORMANCE PREDICTION THROUGH SINGLE RATE KINETICS

To evaluate the validity of applying single rate first order or Michaelis-Menten type kinetics for anaerobic digester design, the operational results from Chapter 7 were juxtaposed to the single rate kinetic models presented in Chapter 8. Chapter 9.1 discusses the data fit in the fundamental Michaelis-Menten and first order kinetic approaches through a sensitivity analysis considering data quality. Chapter 9.2 details the fit of the practical data to both models analyzing digester efficiency and digester effectiveness. Chapter 9.3 describes the effect of reaction kinetics on digester design. Chapter 9.4 presents a case study on digester design for tanks in series and discusses the potential advantages of introducing Michaelis-Menten type kinetics as a design expansion alternative. Chapter 9.5 discusses common and necessary expansions of a design approach for anaerobic digesters identifying its possibilities and limitations. It discusses design variations for decoupling sludge retention time and hydraulic retention time.

9.1. SENSITIVITY ANALYSIS OF SINGLE RATE KINETICS

Roels (1982) argues that, in principle, several unstructured growth models can adequately describe the dependency between substrate and specific growth rate. A distinction between kinetic equations is

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only possible if accurate substrate concentrations are measured. This becomes quite challenging when concentrations are very low. In the case of environmental processes, such as anaerobic digestion of WWTP sludge, a further complication of accurate substrate concentration measurement is the uncertainty of the substrate composition. Only sum parameters such as total volatile solids or chemical oxygen demand are available. Combine this with the many different metabolic pathways interacting in the anaerobic digestion process and the fact, that in practice, WWTPs only reach a pseudo stationary state, since, even under (technically) constant operating conditions, the sludge quality at the inflow varies constantly.

A significant challenge analyzing data from full-scale plants is data accuracy. As introduced in Chapter 0 and presented in Chapter 6, the variation of inflow volume and concentration result in a broad range of input values, instead of homogeneous data sets. Thus, it is likely, that a range of proposed models can be statistically plausible to fit these data sets. This chapter evaluates the quality of the data sets presented in Chapter 7 and discusses how well they fit the proposed models of Chapter 8.

Several authors argue that the rate limiting step for anaerobic digestion of particulate sludge is a first order type kinetic hydrolysis, while others suggest Michaelis Menten type kinetics and some focus on surface dependent models. Each of these kinetic approaches has sensible ranges and applications.

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In principle, Michaelis-Menten type kinetics and first order kinetics can be interpreted as two conditions of the same mechanistic model (Figure 1). At low substrate concentrations ($K_C \gg C_A$), the specific biomass growth rate, and consequently the substrate consumption rate ($r_A = Y \cdot r_C \Rightarrow r_A = (Y \cdot k_{C_{max}}/C_M) \cdot C_A$), is directly proportional to the substrate concentration ($k_C \propto C_A$) (Eq. 95). This results in pseudo first order kinetics for the substrate consumption rate (r_A). At higher substrate concentration, a Michaelis-Menten type hyperbola (Eq. 94) describes the specific biomass growth rate. (As seen in Ch. 4.1.4, at extremely high substrate concentrations, specific biomass growth rate would be independent of substrate concentration (Eq. 96) resulting in "0" order kinetics.) Particle size and particle structure are the drivers to select a surface dependent models for digester design and might have to be considered in case the simple kinetic approaches are not satisfactory.

One method to evaluate the fit of data into Michaelis-Menten type kinetics or first order kinetics is by plotting the biodegradable substrate concentration as a function of the specific biomass growth rate (Figure 1). Assuming a CSTR in steady state, and approximating inflow biomass concentration to "0", the specific biomass growth rate will be equal to the inverse of the hydraulic retention time ($k_C = 1/\text{HRT}$), allowing the determination of k_C in a rather simple manner. The determination of the biodegradable substrate concentration, however, is quite challenging for WWTP sludge. The biodegradable fraction of a sludge is usually not readily available. Its determination

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through BMP tests (HOLLIGER et al., 2016, RAPOSO et al., 2011; VDI, 2014) is very work intensive and not routine on WWTPs. The related parameter available on WWTPs is the total volatile solids concentration that also includes a non-biodegradable recalcitrant organic fraction and biomass.

The raw sludge added to the anaerobic digesters is usually composed of a fraction of primary sludge and a fraction of waste activated sludge. As shown in Table 9, the degradability of primary and waste activated sludge are quite different, at 70 % and 45 % respectively. Furthermore, this degradability presents a range. Primary sludge can be highly degradable, e.g. if retention times in the pipelines are short. Conversely, PS is less degradable if wastewater starts to decompose in the long pipelines or even in the conus of the primary settling tank. Biodegradability of WAS depends significantly on sludge age. The higher the sludge age, the less biodegradable it is, in the extreme case WAS can be completely degraded aerobically and only marginally contribute to biogas production. Thus, a range of 10 % variation in potential degradation was assumed, when determining biodegradable substrate in the analyzed anaerobic digesters.

Figure 35 presents the estimated substrate concentrations within the analyzed anaerobic digesters as a function of the inverse of the hydraulic retention time, assumed the observed biomass growth rate k_C . The k_C value of 0.05 1/d corresponds to 20 days hydraulic retention time, while the k_C value of 0.20 1/d corresponds to 5 days

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hydraulic retention time. High load digesters are located between k_c values of 0.1–0.2 1/d, while conventional digesters are located at k_c values below 0.05 1/d. The precision of substrate concentration in the reactor is quite inaccurate, given the challenge of actually measuring biodegradable substrate in actual WWTP sludge samples, especially on a regular basis. Substrate concentration values below zero are not shown, given that this does not have a physical significance.

There is no obvious linear (or otherwise) dependency between the specific biomass growth rate and biodegradable volatile solids concentration for the different WWTPs. However, a correlation between the specific biomass growth and substrate concentration in the digesters of WWTPs CD 2, CD 3, CD 5, CD 7 (a-c), HLD 4 and HLD 1 (a-c), could be interpreted. Some relationship between digesters CD 4, CD 5 and CD 7 (a-c) might also be identified. Digesters CD 25 °C “a” and CD 25 °C “b” stage as outliers.

Figure 35 exemplifies these correlations as a “pseudo” first order kinetic and a Michaelis-Menten type kinetic. The full lines represent the Michaelis-Menten type kinetic, while the dashed lines represent the corresponding “pseudo” first order kinetic. The two presented correlations differ solely by the k_c value.

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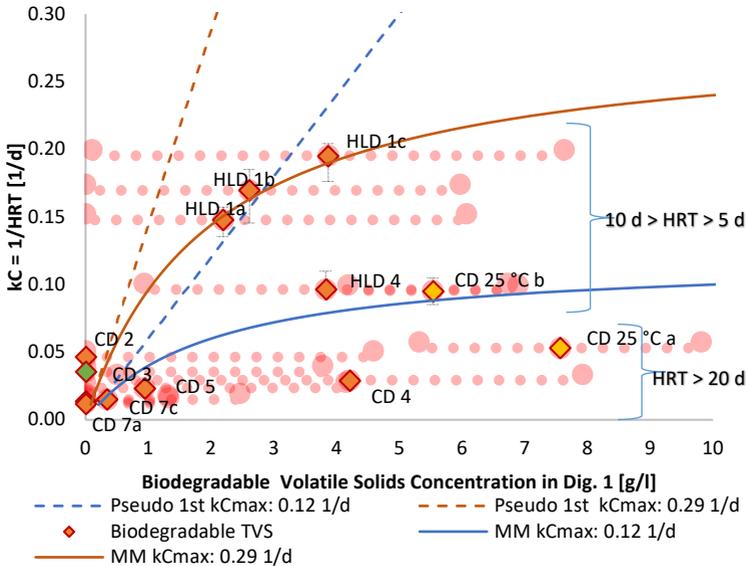


Figure 35: Overlap of kinetic models and estimated biodegradable substrate concentration in digester 1 as a function of the biomass growth rate assuming CSTR ($k_c=1/HRT$) and no biomass at inflow. C_M 2 g/l; Y 0.05. Horizontal dotted line shows possible range of biodegradable substrate, vertical whiskers show the inverse of the HRT variation.

Based on the data both approaches could be acceptable, e.g., pseudo first order kinetics with k_{Cmax} 0.12 1/d and Michaelis-Menten type kinetics with k_{Cmax} 0.29 1/d could describe the degradation of HLD 1. Based on the mechanistic reasoning the Michaelis-Menten type kinetic approach presents a couple of advantages, namely prediction of washout and performance under different inflow conditions.

9.2. MODELING DIGESTER PERFORMANCE (FIT OF OPERATIONAL DATA IN THEORETICAL MODEL)

The data from the analyzed anaerobic digesters were overlapped with the presented kinetic models. These results were fitted to the design recommendations from literature, considering a single rate determining step ruled by first order kinetics; and to the model proposed in this thesis of a single rate determining step ruled by Michaelis-Menten type kinetics. In the case of first order kinetics the benchmark digester design according to DWA (2014) is presented considering a first order constant of 0.26 1/d. In the case of Michaelis-Menten type kinetics, the selected half velocity constant C_M is 5 g/l and the specific biomass growth rate, $k_{C_{max}}$ is 0.36 1/d. Sludge was assumed to be composed of equal shares of primary and waste activated sludge. The primary sludge is considered to have 70.0 % degradability and WAS degradability is considered to have 45.0 % degradability, resulting in an overall TVS degradability of 57.5 %. Model digester temperature was set at 35 °C.

9.2.1. DIGESTER EFFECTIVENESS: BIOGAS PRODUCTION AND TVS REMOVAL

Biogas production per total volatile solids added and the fraction of total volatile solids removed describe digester effectiveness. Figure 36 shows the results from the specific biogas production per TVS added for one digester (red diamonds) and two digesters in series (blue squares), overlapped with the specific biogas production per

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TVS added for the first order kinetic model considering one digester (red line) and two digesters in series (blue line). Figure 37 presents the results for the Michaelis-Menten kinetic model. It is assumed that the biogas measurement on the WWTPs was not corrected to fit norm conditions and that the registered biogas volumes are under operational conditions. Instead of adapting the measured biogas values assuming unknown temperatures, model data was corrected based on the fundamental law of gases, to portray the biogas volume at 35 °C.

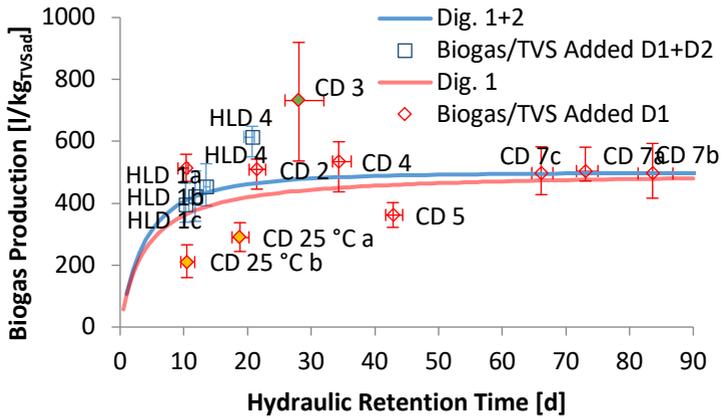


Figure 36: First order model fit of the specific biogas production per added TVS as a function of hydraulic retention time for one and two tanks in series (k_{1st} 0.26 1/d, T 35 °C, b_{TVS} 57.5 %, $Y_{C/bTVS}$ 0.05)

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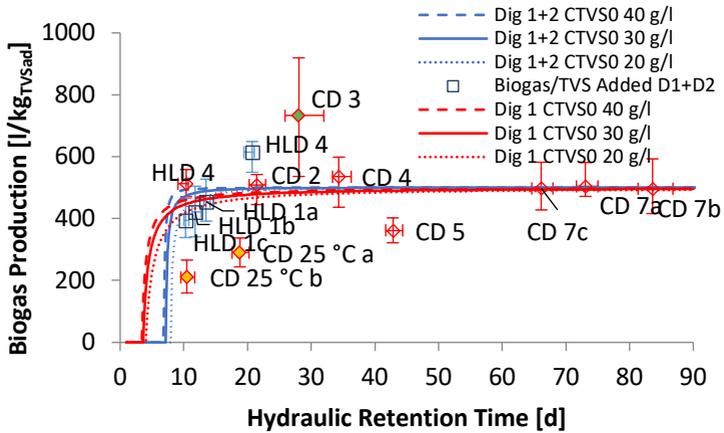


Figure 37: Specific biogas production Michaelis-Menten type kinetic design (C_{TVS0} 20, 30, 40 g/l, b_{TVS} 57.5 %, CM 5 g/l, k_{Cmax} 0.36 1/d, $Y_{c/bTVS}$ 0.05)

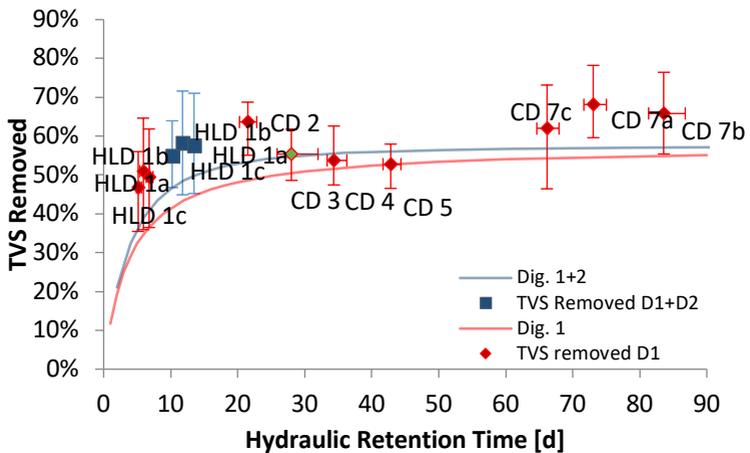
The first order kinetic model and the Michaelis-Menten type kinetic model accurately identify the total biogas production per added substrate for WWTPs CD 7. None describes the performances of CD 3 and CD 5. The performance of the primary digesters of WWTP CD 2, CD 4 and HLD 4 are slightly underestimated by the Michaelis-Menten type kinetics and significantly underestimated by first order kinetics. At lower HRTs, underestimation of digester performance is greater than at higher HRTs.

First order kinetics seem to quite accurately predict the performance of the two digesters in series of WWTP HLD 1, while Michaelis-Menten type kinetics model seem to slightly overestimate them. The performance of WWTP CD 3 is significantly underestimated under

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the presented conditions. This is expected, given that WWTP CD 3 receives concentrated co-substrate. Both models significantly overestimate the performance of WWTP CD 5; this is likely to poor reactor mixing, given WWTP CD 5 only presents an external pumping cycle. Both models also underestimate the performance prediction of WWTP HLD 4 under the current conditions. WWTP CD 25 °C does not fit the presented curves, even when adjusting temperature values the data does not fit.

Figure 38 presents the results for the total volatile solids removal for one digester (red diamonds) and two digesters in series (blue squares) from the evaluated WWTPs, overlapped with the TVS removal for the first order kinetic model considering one digester (red line) and two digesters in series (blue line). Figure 39 presents the results for the Michaelis-Menten type kinetic model.



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Figure 38: First order model fit of the TVS removal as a function of hydraulic retention time for one tank and two tanks in series (k_{1st} 0.26 1/d, T 35 °C, $bTVS$ 57.5 %, $Y_{C/bTVS}$ 0.05)

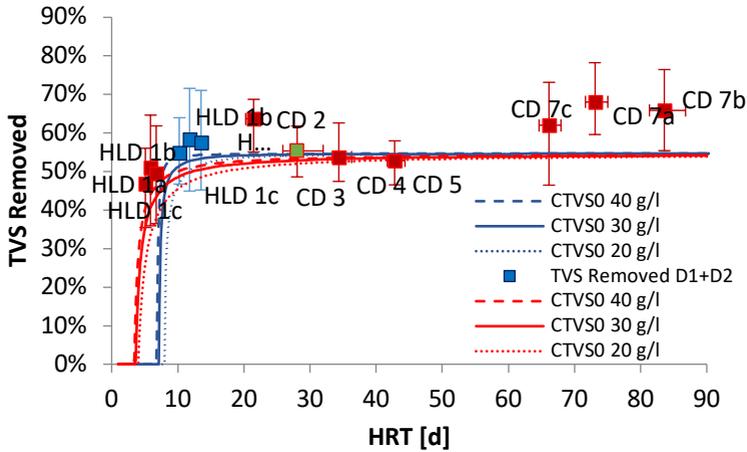


Figure 39: Monod model fit of the TVS removal as a function of hydraulic retention time for one tank and two tanks in series (C_{TVS0} 20, 30, 40 g/l, $bTVS$ 57.5 %, C_M 5 g/l, k_{Cmax} 0.36 1/d, $Y_{C/bTVS}$ 0.05)

Both kinetic approaches allow a good prediction of the TVS removal for WWTPs CD 4 and CD 5. The first order model underestimates the solids removal for WWTP CD 3. However, the Michaelis-Menten type kinetic model results in a good prediction. WWTPs CD 2 and CD 7 present a better solids removal than expected by the models. This can be explained by the higher primary sludge fraction in the feed. First order kinetics underestimate the performance of WWTP HLD 1 that operates under hydraulic retention times of 5 – 7 days for each

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digester, but Michaelis-Menten type kinetics present a good fit. Here, WWTP HLD 1 is moving at the verge of washout.

The use of Michaelis-Menten kinetics implies that the feed concentration to the reactor is relevant to its performance. Most of the evaluated WWTPs presented relatively high solids concentration at the inflow. One important exception was WWTP CD 25 °C, especially under condition “b”. This WWTP at 10 days of HRT presented poor performance, also in comparison to other WWTPs with similar HRTs, such as WWTP CD 1 and HLD 4. From these three, WWTP HLD 4 presented the best performance. It also presented the highest concentration of total volatile solids at the inflow. It is likely that the effect of the solids concentration is only small, especially under typical digester operation conditions, e.g. at 20 days HRT for the suggested Michaelis-Menten type kinetics the removal improves from 53 % to 55 % and at 10 days HRT from 45 % to 50 %. However if the boundary conditions are changed, e. g. through the improvement of raw sludge thickening, the designer should be able to describe the effect of increased solids concentration on the reactor performance.

9.2.2. DIGESTER EFFICIENCY: REACTION RATE

Reactor specific biogas production and the reactor specific solids removal characterize digester efficiency. Figure 40 presents the results for the first order kinetics. It shows the reactor specific biogas production for one digester (red lines). Figure 41 that shows the results for two identical digesters in series (blue lines), overlapped

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with the results from the evaluated WWTPs (red diamonds for the first digester and blue squares for the combined first and second digester). Figure 42 and Figure 43 present the results for the Michaelis-Menten kinetic model. Considering that, WWTP CD 3 to CD 7 only have a primary digester, the high hydraulic retention times are not shown in Figure 41 and Figure 43 and the abscissa is reduced to 30 days for better visualization.

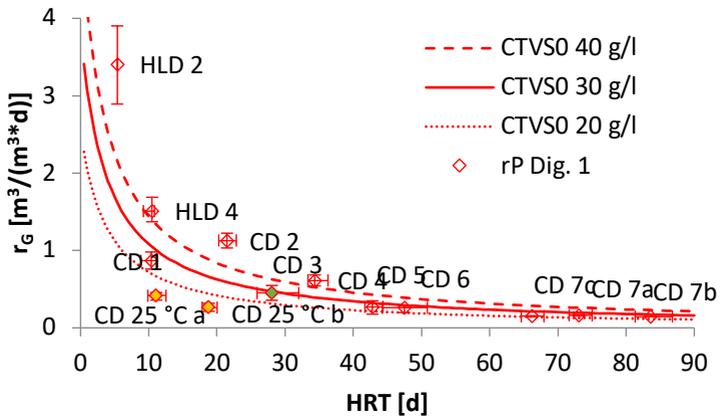


Figure 40: First order kinetics fit at 35 °C for biogas production rate in one CSTR (k_{1st} 0.26 1/d, T 35 °C, bTVS 57.5 %, $Y_{C/bTVS}$ 0.05)

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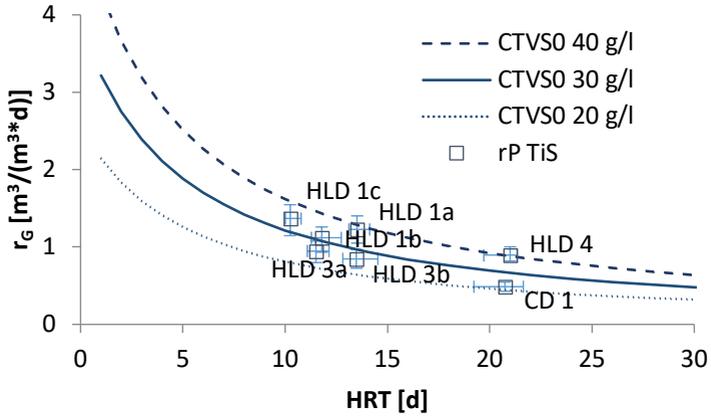


Figure 41: First order kinetics fit at 35 °C for apparent biogas production rate for two CSTRs tanks in series (TIS) (k_{1st} 0.26 1/d, T 35 °C, bTVS 57.5 %, $Y_{C/bTVS}$ 0.05)

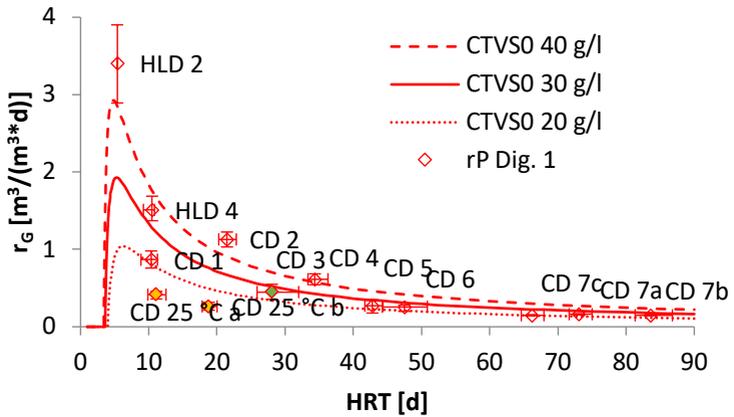


Figure 42: Michaelis-Menten type kinetics fit at 35 °C for biogas production rate in one CSTR (C_{TVS0} 20, 30, 40 g/l, bTVS 57.5 %, C_M 5 g/l, k_{Cmax} 0.36 1/d, $Y_{C/bTVS}$ 0.05)

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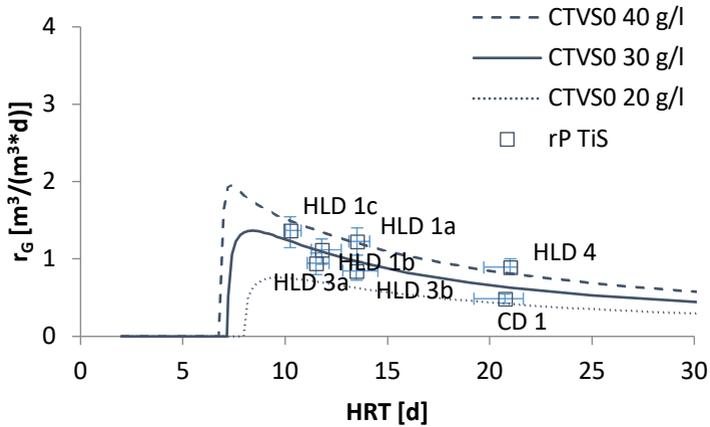


Figure 43: Michaelis-Menten type kinetics fit at 35 °C for apparent biogas production rate for two CSTRs tanks in series (TiS) (C_{TVS0} 20, 30, 40 g/l, b_{TVS} 57.5 %, C_M 5 g/l, k_{Cmax} 0.36 1/d, $Y_{C/bTVS}$ 0.05)

The specific biogas production in WWTP CD 2 and HLD 2 deserve particular attention. Current design conditions underestimate both of them. To fit this reaction rate in the first order approach, the inflow total volatile solids concentration would have to be increased up to 60 g/l of TVS. This implies a total solids input concentration of about 85 g/l of total solids. This is not the case neither for WWTP CD 2 nor for WWTP HLD 2. Their total solids concentrations lie at 50 g_{TS}/l and 60 g_{TS}/l respectively. To fit the current Michaelis-Menten type kinetics, the substrate inflow concentration would have to be increased to 45 g/l for WWTP HLD 2 and to 50 g/l for WWTP CD 2. This would mean 64 g_{TS}/l at the inflow for WWTP HLD 2 and 71 g_{TS}/l for WWTP CD 2, which is closer to reality.

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WWTP 25 °C presents low reaction rates compared to the other WWTPs, even though they still seem to fit the model. Operational condition “a” presents a TVS concentration fed to the reactor of 20 g/l and operational condition “b” a TVS concentration fed to the reactor of about 10 g/l. In reality, considering the lower operational temperature of this digester, lower $k_{C_{max}}$ values and higher C_M values are expected. This would result in a better model fit.

Next to the specific biogas production rate, the specific solids removal rate was evaluated. Figure 44 presents the results for the first order kinetics. It shows the reactor specific solids removal rate for the first digester (red lines) and the second digester (green lines). Figure 45 shows the results for two identical digesters in series (blue lines), overlapped are the results from the evaluated WWTPs (red diamonds for the first digester, green triangles for the second digester and blue squares for the combined first and second digester). Figure 46 and Figure 47 present the results for the Michaelis-Menten kinetic model. (ANNEX 13.7.2 shows the results for total solids concentrations of Figure 44 and Figure 46).

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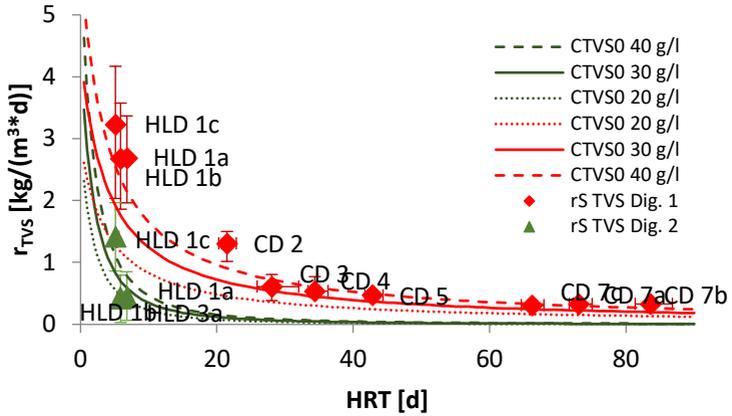


Figure 44: First order kinetics fit at 35 °C for substrate removal rate in the first and second CSTRs (k_{1st} 0.26 1/d, T 35 °C, b_{TVS} 57.5 %, $Y_{C/bTVS}$ 0.05)

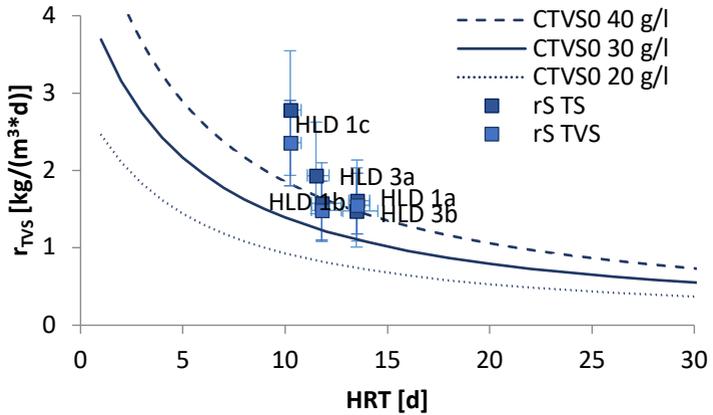


Figure 45: First order kinetics fit at 35 °C for apparent substrate removal rate for two CSTRs in series (k_{1st} 0.26 1/d, T 35 °C, b_{TVS} 57.5 %, $Y_{C/bTVS}$ 0.05)

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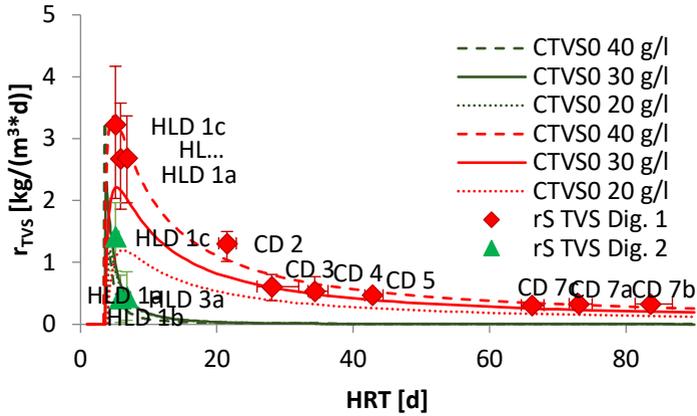


Figure 46: Michaelis-Menten type kinetics fit at 35 °C for substrate removal rate in the first and second CSTRs (C_{TVS0} 20, 30, 40 g/l, b_{TVS} 57.5 %, C_M 5 g/l, k_{Cmax} 0.36 1/d, $Y_{C/bTVS}$ 0.05)

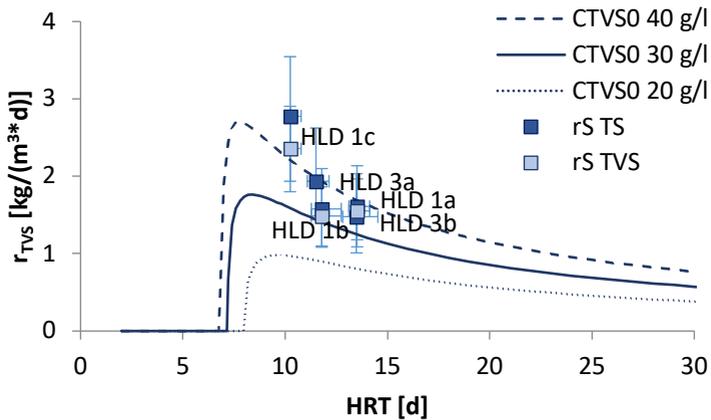


Figure 47: Michaelis-Menten type kinetics fit at 35 °C for apparent substrate removal rate for two CSTRs in series (C_{TVS0} 20, 30, 40 g/l, b_{TVS} 57.5 %, C_M 5 g/l, k_{Cmax} 0.36 1/d, $Y_{C/bTVS}$ 0.05)

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The data from the WWTPs CD 3, 4, 5 and 7, operated at hydraulic retention times above 25 days, seem to fit both kinetic approaches when evaluating the total solids removal rate. Both kinetic models underestimate the substrate removal rate from WWTP CD 2. At lower HRT WWTP HLD 1 and HLD 3 seem to present a better fit in the Michaelis-Menten type kinetic approach, the first order kinetics underestimates the overall reaction rates in the first digester.

The operational condition HLD 1 “c” presents a reaction rate in the second digester of $2.2 \text{ kg}/(\text{m}^3 \cdot \text{d})$ at 5.1 days of HRT. This condition is likely a consequence of operating the digesters close to the washout at extremely high organic loading rates. First order kinetics cannot describe this condition. In this case, the organic load is too high, exceeding the volumetric solids removal capacity of the primary digester. A large part of the degradable organic material flows to the second digester. Observing Figure 44 and Figure 46 it is possible to note that the observed reaction rate of $2.2 \text{ kg}/(\text{m}^3 \cdot \text{d})$ would only be reached at 2.5 days for the first order kinetics and is reached at about 5 days in the case of the presented Michaelis-Menten type kinetics.

Observing WWTP HLD 2 in Figure 42 and WWTPs HLD 1 and HLD 3 in Figure 46 under the Michaelis-Menten type kinetics it can be argued that these digesters are operating close to its maximum rate performance. Any small variation of the hydraulic retention time or substrate feed concentration would have a significant effect on the reaction rate. To warrant a good performance, a design

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recommendation in this case would be to assure constant feed properties through proper installations such as equalization tanks. This condition is not so explicit when first order kinetics are used for digester design.

The single rate design kinetic models presented in this chapter show that for long hydraulic retention times the selected kinetic approach is not particularly relevant. First order kinetics as well as Michaelis-Menten type kinetics will describe the digester appropriately. At lower hydraulic retention times however, the Michaelis-Menten type kinetics showed a better fit to the observed results. The possibility of considering maximum reaction rates and washout phenomena, combined with a good level of accuracy allow an expanded understanding of the optimization potential of an anaerobic digester.

9.3. EFFECT OF REACTION KINETICS ON CSTR DIGESTER DESIGN RECOMMENDATIONS

Next to the civil engineering aspects of anaerobic digester design recommendations, reaction kinetics so far have only played a minor role in anaerobic digester design. The DWA M368 first included aspects of reaction kinetics in their review in 2014, by adding simple first order kinetics. Metcalf and Eddy in their fourth edition (2004) write, *“Ideally, the design of anaerobic sludge digestion should be based on an understanding of the fundamental principles of biochemistry and microbiology [...]. Because these principles have not been appreciated fully in the past, a number of empirical methods*

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have been used." The fifth edition (2014) describes biomass growth and rate of particulate and soluble substrate utilization, however, with no actual consequences towards digester design. This chapter analyzes relevant consequences of digester design based on selected conditions described through the kinetic approach.

9.3.1. WASHOUT PREDICTION

Continuously operated reactors present two extreme alternatives: the continuous stirred tank reactor (CSTR) and the plug flow reactor. The kinetic description of a given reaction will support the design engineer to select the optimal reactor or reactor combination. One fundamental advantage of using Michaelis-Menten type reaction kinetics is that it describes the relation between substrate and biomass/enzymes, more specifically the ability to predict biomass or enzyme washout. Thus, if the design engineer selects a plug flow reactor, or several tanks in series with very short individual hydraulic retention times, the Michaelis-Menten type kinetic approach would indicate the demand for biomass recirculation to avoid washout. Sludge recirculation on plug flow reactors is common practice on digesters for energy crops and municipal solid waste that operate at high organic loading rates.

9.3.2. EFFECT OF SUBSTRATE CONCENTRATION AT INFLOW

Consider the shorter hydraulic retention times (below 20 days HRT) of Figure 33 and Figure 34, presented as Figure 48 and Figure 49. As

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seen in Ch. 8, (biodegradable) volatile solids concentration at the inflow does not influence the CSTR performance for first order kinetics; however, it significantly affects the minimum design HRT if Michaelis-Menten type kinetics apply.

The design engineer defines, that the anaerobic digester has to remove some amount of biodegradable volatile solids (e.g. 85 % - blue and red dots on Figure 48). If she wants to build a reactor, that operates under maximum load at 7 days hydraulic retention time, she needs to guarantee, that under these conditions volatile solids concentration at the inflow reach the necessary 40 g/l (assuming 57,5 % biodegradability). This reasoning would not be sensible in the first order kinetic approach. Any sludge concentration would reach the necessary degradation at about 20 days HRT. It would be possible to argue that even a very thin sludge, e.g. 10 g_{TVS}/l, would reach the necessary decomposition at 20 days HRT and produce the expected mass of biogas.¹⁴

¹⁴ Granted it would not make economic sense because sludge volumes would be extremely large.

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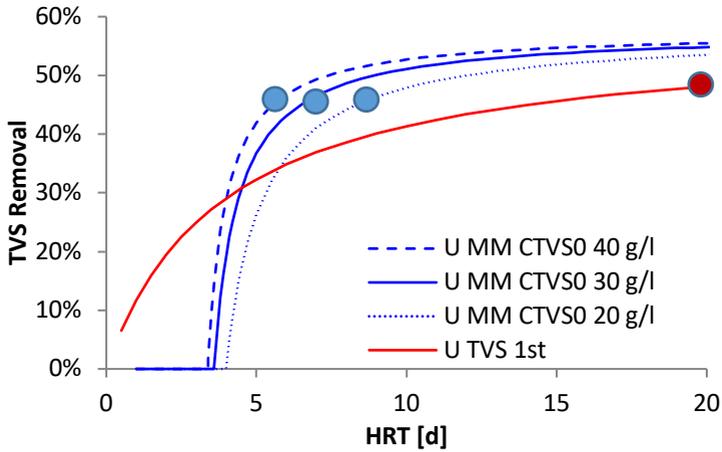


Figure 48: Digester design overlap for total volatile solids removed at benchmark parameters from Table 25 and Table 27

The technology for sludge thickening, as well as sludge management have to be designed in a manner to ensure proper digester functioning. Experience shows that primary sludge can reach the necessary solids content through proper PS management and static thickening; however, this is not a given (Figure 14). WWTP operators started increasing the automation of primary sludge removal from the primary settling tanks (HLD 3, CD 2, CD 3, and CD 4) and even mechanically thickening primary sludge (HLD 1). Likely, static sludge thickening for WAS, will not be sufficient to reach high volatile solids concentration (CD 1, CD 7 and CD 25 °C have static thickening and do not reach high solids concentrations of raw sludge to the digester), demanding mechanical sludge pre-thickening. After pre-thickening, most of the sludge fed to the HLDs reach 35 g/l to 40 g/l TVS

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concentration on a regular basis; conventional digesters CD 2, 3 and 4 fulfill this condition (Figure 17).

In summary, while for first order kinetics, sludge thickening reduces reactor volume, for Michaelis-Menten type kinetics it is necessary to warrant the desired function.

Reaction rate increases with increase of substrate concentration at the inflow and reduction of hydraulic retention time. Even though inflow substrate concentration affects both kinetic approaches, Michaelis-Menten Type kinetics reach 85 % substrate degradation under different operational conditions (blue dots on Figure 49).

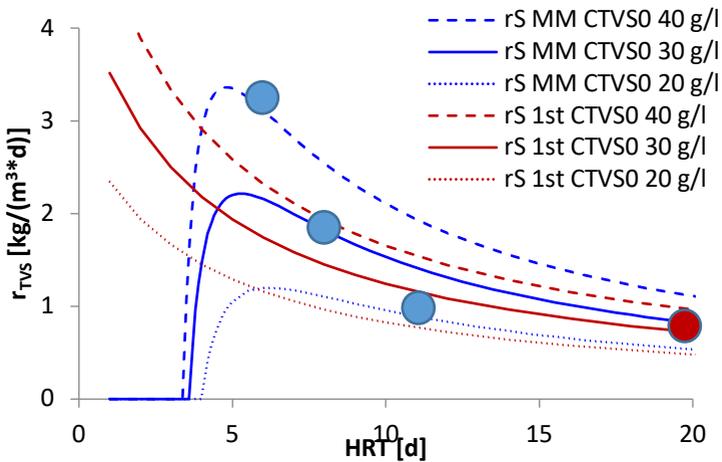


Figure 49: Digester design for substrate removal reaction-rate at benchmark parameters from Table 25 and Table 27

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Take the reaction rate for 40 g_{TVS}/l at inflow and 7 days HRT. Here solids degradation rate lies at about 2.8 kg_{TVS}/(m³*d) and reactor specific biogas production is 2.2 m³/(m³*d). At 20 days HRT, reaction rate and biogas production for the same input concentration would lie at 1.1 kg/(m³*d) solids removal and 0.9 m³/(m³*d) biogas production. At higher specific reaction rates, changes in the bulk properties will have more immediate effects than at lower specific reaction rates. Thus, the design engineer has to include solutions to manage potential bulking and foaming situations, as well as reactor mixing at slightly increased solids concentration.

The produced biogas flows through the reactor headspace towards a biogas reservoir or the biogas users. If the biogas does not leave the reactor, it accumulates in the bulk reducing overall density. Schäfer et al. (2016) observed the effect of decreased density due to increased reaction rates in their egg shaped reactors. Their anaerobic digesters are set in series and connected to each other through an overflow shaft. The operation under increased loading rates resulted in an increase of specific biogas production rate and a volume increase in the first reactor. The small overhead space in the first reactor combined with the increased bulk volume resulted in a reactor spill before the content could overflow to the second reactor. Lower density in the first reactor was pinpointed as one of the origins of the problem.

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For new digesters, the design engineer has three design adaptations to consider:

- 1) build a larger headspace to manage volume increases without spilling,
- 2) remove the fluid from the reactor through a pumping system instead of an overflow and
- 3) increase mixing energy to increase biogas upward velocity to allow biogas to leave the reactor faster and higher shear forces to separate biogas from particles,

In all cases, cost and operability factors need consideration.

Conventional digester design typically presents a very small headspace (Figure 6), with the exception of the pancake digesters common in the USA. The small headspace design focuses on ensuring high liquid agitation and suppression of foam formation, as well as improved mixing conditions in the bulk. (WEF, 2009). The disadvantage of the narrow gas dome is, that in case of significant foam formation or bulking (e.g. due to increased specific biogas production) immediate overflow occurs.

The WWTP of CD 1 was originally equipped with a cylindrical digester with conical top and bottom and mixing through gas injection, the operator decreased the reactor volume to the edge of the cylinder to allow the digester to operate even at foaming or bulking events. High load digesters designed as “Schwarking-Uhde” reactors or as loop

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reactors present at least one meter of headspace to manage foaming and bulking events, improving operational security. A larger headspace would allow increased operational security and some flexibility in the active reactor volume. However, if selecting an egg shaped reactor, the design engineer would have to re-consider mixing dynamics within the digester.

The most cost effective method to remove sludge from anaerobic digesters is through an overflow system. However, this method only allows little operational control. Sludge removal through a pumping (or valve) system presents several advantages: it reduces issues with variation in the bulk density; it allows the operator to control the liquid level within the digester and potentially remove scum layers from the system. When executing the economic analysis, the design engineer will choose between operability and smaller capital expenditures.

Biogas flows upward in the digester. However, its upward velocity is not necessarily sufficient to ensure effective biogas removal, resulting in bulking of the digester. Increased biogas production rates will result in increased digester bulking. Digester mixing systems thus have to be designed to increase the upward velocity, e.g. biogas injection, or/and increase the shear forces that separate biogas from the bulk, e.g. draft tubes and mechanical stirring.¹⁵ At higher biogas

¹⁵ Draft tube systems produce shear forces on the gas-liquid surface.

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production rates, the design engineer will have to consider the increased reaction rate when designing the mixing system.

At higher inflow concentrations and shorter hydraulic retention times the increased solids removal rate will produce a similar concentration of biodegradable volatile solids. However, the concentration of fixed solids and non-biodegradable volatile solids will result in **increased solids concentration** in the digester and outflow, with all the consequences to the fluid properties. Figure 50 shows the estimated solids concentration for benchmark parameters considering first order and Michaelis-Menten Type kinetics, including recalcitrant solids, non-degradable volatile solids and biomass.

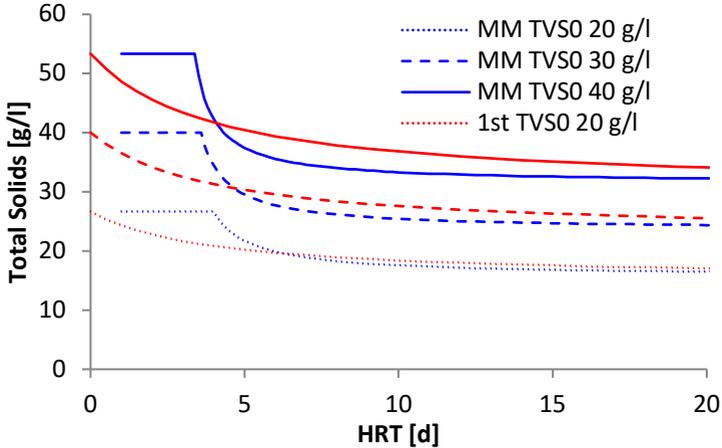


Figure 50: Total solids concentration in reactor and at outflow (including non-biodegradable volatile solids) for benchmark parameters of first order kinetics (red) and Michaelis-Menten type kinetics (blue)

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The different solids concentrations can significantly affect the physico-chemical properties of the bulk material in the reactor, such as viscosity, thixotropy and density. These parameters will affect the fluid velocity, fluid properties and consequently the necessary mixing energy within the reactor. The design engineer should focus on planning a reactor mixing that: reaches acceptable CSTR conditions based on the sludge fluid properties, avoids substance accumulation and short-circuiting, but does not affect the syntrophic anaerobic clusters of methanogenesis.

9.3.3. DESIGN RANGE FOR DIGESTERS WITH SHORTER HRT BASED ON MICHAELIS-MENTEN TYPE KINETICS

In the digester design process, the engineer needs to decide which type of kinetic approach is sensible for its application. Usually, the goal is to reach maximum degradation of substrate and maximum production of biogas at the minimum possible investment and operational costs. Revenue from biogas and sludge disposal costs will influence the latter. The square on Figure 51 shows a suggestion of the design range for high load digesters based on Michaelis-Menten type kinetics.

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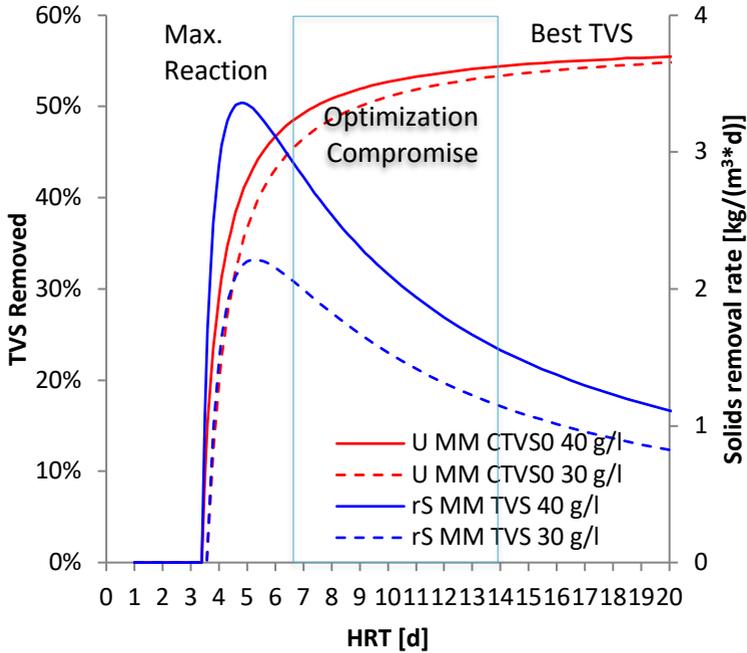


Figure 51: Range of current design recommendations for anaerobic digesters based on Michaelis-Menten type kinetics

At maximum reaction rate (blue lines) product formation (biogas and biomass) reaches its maximum production per unit time. Under this condition, biodegradation is at only about 65 % to 70 % of its potential, resulting in increased sludge volumes and lower biogas production. As seen in Ch. 8.3, this condition is also more susceptible to changes and instability if any kinetic parameter is affected, e.g. due to an acute inhibition from a toxic shock. At maximum solids degradation (red lines) significant increases in HRT are necessary to

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reach further improvement. No significant gain in increasing HRT, while investment and operational costs start to increase significantly, e.g. through larger reactors, larger aggregates at the plant and increased heating costs.

The design engineer needs to specify the optimization curve based on the demanded solids removal fraction, current and predicted sludge disposal costs, biogas revenue and climate conditions. Furthermore, the design engineer also has to evaluate the range of operations of a particular digester. Next to the extreme condition of total load at maximum design capacity, pumping, piping, heating, mixing, gas storage and processing systems also have to attend the minimum design conditions, when sludge loads are small and flows are minimal.

9.4. CASE STUDY: SHORT HRT DIGESTER WITH TANKS IN SERIES

Four of the evaluated WWTPs have data on the performance of two tanks in series. The single rate models were compared to the input data from the WWTPs HLD 1, HLD 3, HLD 4 and CD 1. Given that each sludge has a specific characteristic, the kinetic constants k_{1st} , C_M and k_{Cmax} were adjusted iteratively to reach the best fit to the experimental data, regarding all available digester performance parameters and maintaining the range presented in literature. Table 28 presents the input data for first order kinetics and Michaelis-Menten type kinetics for each evaluated WWTP. Figure 52 and Figure 53 present the first order kinetic model and the Michaelis-Menten kinetic model adjusted to WWTP HLD 4.

Table 28: Overview of design parameters adjusted to specific WWTPs

Parameter	Units	HLD 1	HLD 3	HLD 4	CD 1
C_{TVS0}	[g/l]	35	35	33	20
bTVS	[%]	62	62	68	62
k_{1st}	[1/d]	0.8	0.8	0.6	0.5
C_M	[g/l]	1.0	1.0	6.0	3.0
k_{Cmax}	[1/d]	0.22	0.22	0.29	0.29

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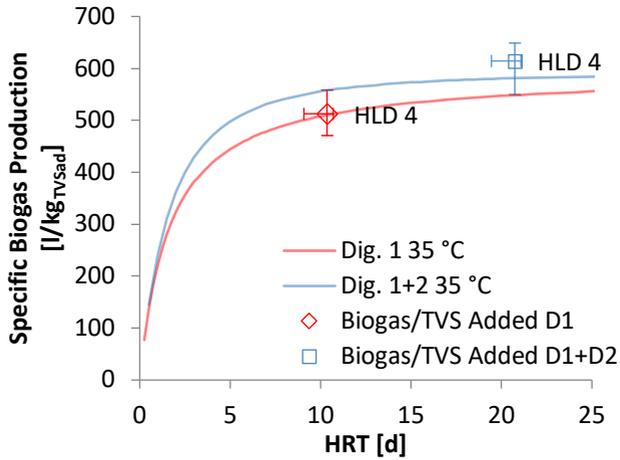


Figure 52: Adjusted specific biogas production for HLD 4 1st Order CSTR, k^{1st} 0.6 1/d, T 35 °C, b_{TVS} 68 %, $Y_{C/bTVS}$ 0.05

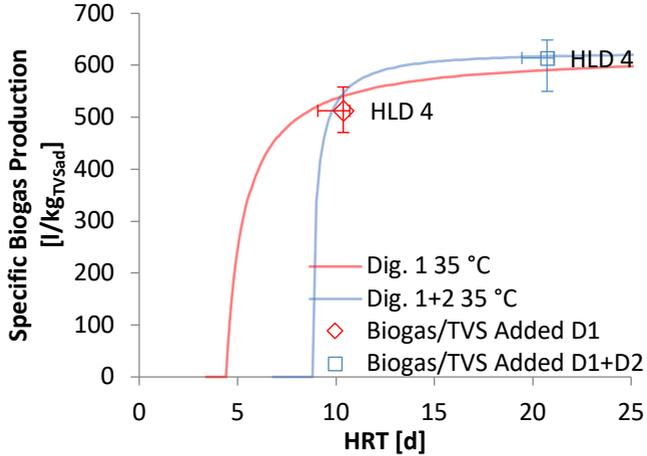


Figure 53: Adjusted specific biogas production for HLD 4 C_{TVSo} 33 g/l, b_{TVS} 68 %, C_M 6 g/l, k_{Cmax} 0.29 1/d, $Y_{C/bTVS}$ 0.05

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It was not possible to describe the performance of the digester with the benchmark parameters for first order and Michaelis-Menten type kinetics. The input substrate to the anaerobic digester is composed of a significant fraction of primary sludge and the activated sludge is well managed, with a sludge age of about 11 days, resulting in a higher biodegradability fraction of 68 %. The Michaelis-Menten type kinetic model parameters C_M and $k_{C_{max}}$ were adjusted iteratively to fit the observed results. Adjustment of the specific biogas production for the first digester was not optimal; however, a compromise between specific biogas production and specific biogas production rate was necessary. Better fit of the latter was considered more relevant, considering the superior data quality of reactor size and biogas production compared to solids added to the digester. It was not possible to adjust the k_{1st} value to reach both observed conditions of the sequencing reactors. Either the first or the combined reactor kinetics could be described. This supports the use of the Michaelis-Menten type kinetic approach.

In Figure 53, it is possible to see that the washout HRT would occur at 4 days HRT for the first digester or at about 8 days for the combination of the first and the second digester. The kinetic approach indicates that the system could be operated at hydraulic retention times down to about 7 days HRT in each digester. Here, the fraction of the sludge decomposed in the second digester would increase slightly compared to current operational conditions. Figure

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52 on the other hand, can be misleading. First order kinetics suggest a relatively good performance at about four days HRT per digester.

Figure 54 and Figure 55 present the biogas production rates for WWTPs HLD 4 and CD 1. A significant difference between WWTP HLD 4 and CD 1 is the feed concentration, while WWTP HLD 4 has an inflow of about 33 g_{TVS}/l, the inflow to WWTP CD 1 is of about 20 g_{TVS}/l.

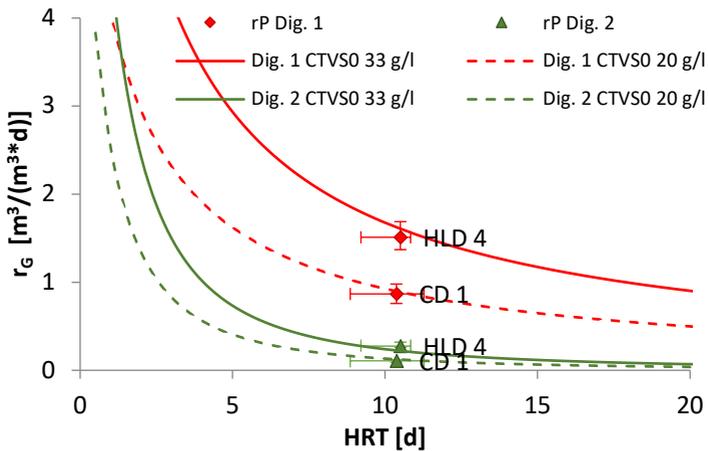


Figure 54: Adjusted specific biogas production rate 1st Order CSTR, k_{1st} 0.6 1/d, T 35 °C, b_{TVS} 68 % HLD 4 and 62 % CD 1, $Y_{C/bTVS}$ 0.05

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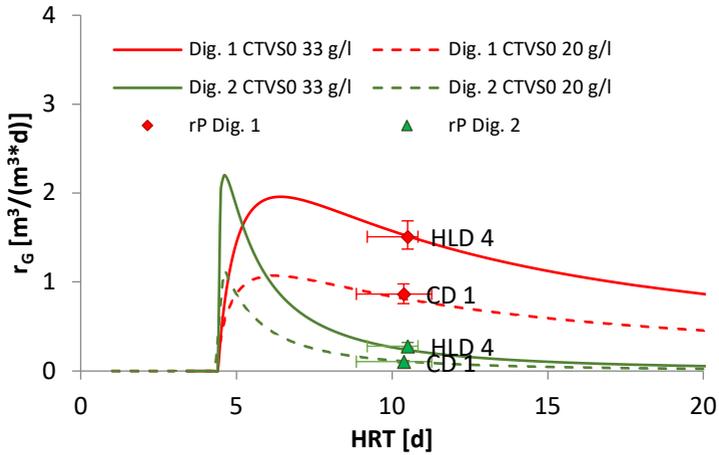


Figure 55: Adjusted specific biogas production rate C_{TVS0} 33 g/l HLD 4 and 20 g/l CD 1, b_{TVS} 68 % HLD 4 and 62 % CD 1, C_M 7 g/l HLD 4 and 3 g/l CD 1, k_{Cmax} 0.29 1/d, $Y_{C/bTVS}$ 0.05

Both cases show the influence of 1) the substrate concentration and 2) biodegradability of the sludge feed over the reaction rate. Figure 55 shows the washout effect at about 4 days for both cases. This is consistent, given that both digesters have the same k_{Cmax} values and the other parameters do not influence washout this significantly. The selected C_M value for WWTP HLD 4 is higher than for WWTP CD 1. The higher C_M value to fit the data can be explained through the primary sludge quality of WWTP CD 1 that is expected to be somewhat better, considering its lower SOR of about $32 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ compared to $39 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ from WWTP HLD 4. The difference in the C_M values explains how the maximum biogas production rate for WWTP HLD 4 reaches about 6.5 days hydraulic retention time in the

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first digester and at about 6 days for WWTP CD 1. The maximum biogas production rate and the washout condition are very close to each other for the second digester. Primary digester operation under these conditions still seems reasonable; the second digester delivers about 15 % to 20 % improvement of the overall performance. An increase in the total biodegradable substrate concentration fed to the reactor would improve the digester efficiency in both cases.

WWTP HLD 1 and HLD 3 operate under slightly higher inflow concentrations than WWTP HLD 4 and at significantly higher organic loading rates. Figure 56 and Figure 57 present the total solids removal for first order kinetic model and the Michaelis-Menten kinetic model adjusted to WWTPs HLD 1, there is no volatile solids removal data for WWTP HLD 3.

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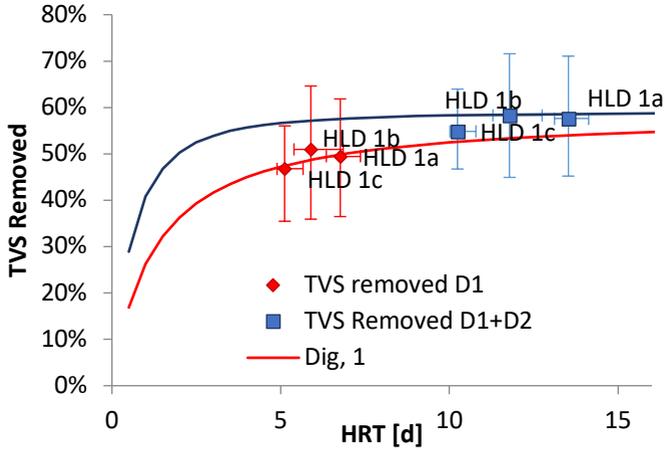


Figure 56: Adjusted specific substrate removal for HLD 1 1st Order CSTR, k_{1st} 0.8 1/d, T 35 °C, bTVS 62 %, $Y_{C/bTVS}$ 0.05

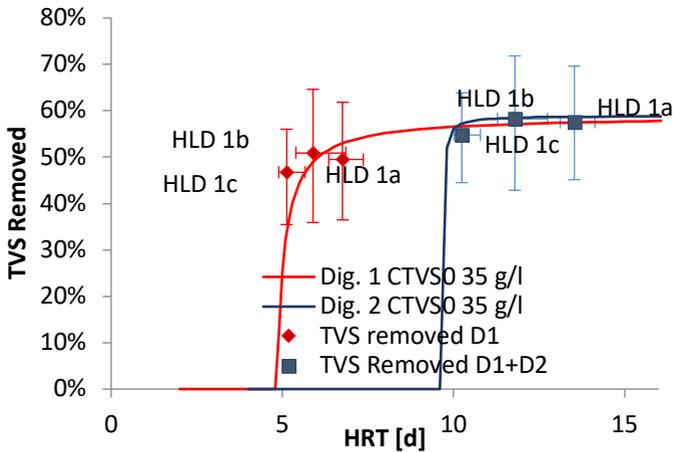


Figure 57: Adjusted specific substrate removal for HLD 1 C_{TVS0} 35 g/l, bTVS 62 %, C_M 1 g/l, k_{Cmax} 0.22 1/d, $Y_{C/bTVS}$ 0.05

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The results for the TVS removal of WWTP HLD 1 can be adjusted to both kinetic approaches. Under the Michaelis-Menten type kinetics in Figure 57, it is possible to observe that WWTP HLD 1 is operating at the verge of operational conditions with respect to HRT. This is possible to observe more in detail when evaluating the reactor specific solids removal rate for each kinetic approach presented in Figure 58 and Figure 59.

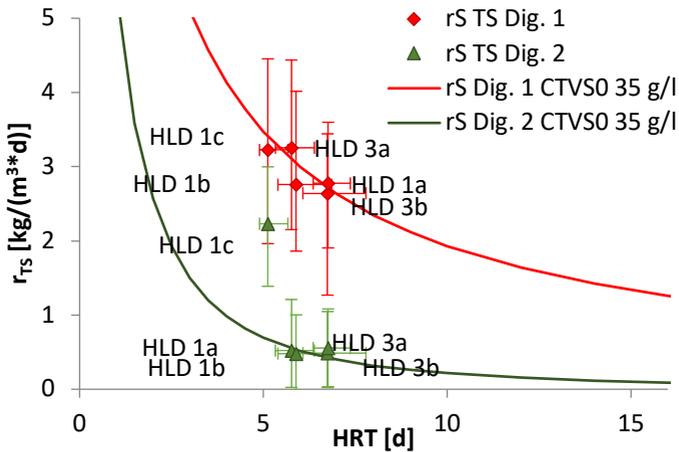


Figure 58: Adjusted specific substrate removal rate for HLD 1 and HLD 3 1st Order CSTR, k_{1st} 0.8 1/d, T 35 °C, bTVS 62 %, $Y_{C/bTVS}$ 0.05

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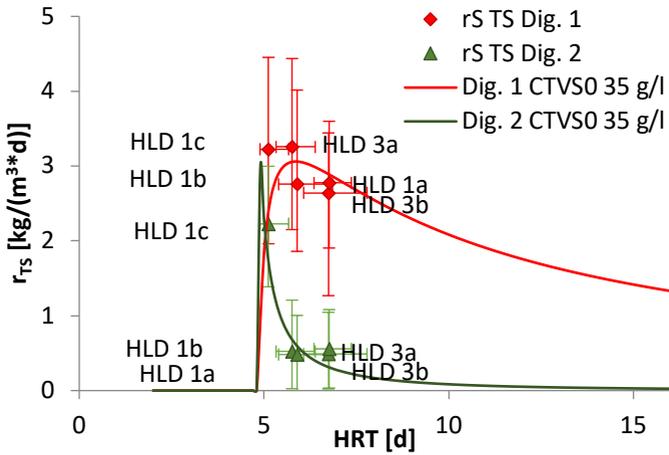


Figure 59: Adjusted specific substrate removal rate for HLD 1 and HLD 3 C_{TVS0} 35 g/l, b_{TVS} 62 %, C_M 1 g/l, k_{Cmax} 0.22 1/d, $Y_{C/bTVS}$ 0.05

It is possible to observe that the first order kinetics in Figure 58 do not predict the high reaction rate in the second digester of WWTP HLD 1 “c”, however the Michaelis-Menten type kinetics presented in Figure 59 shows the spike in the reaction rate. At 5 days hydraulic retention time WWTP HLD 1 “c” removes about 3.2 kg solids per cubic meter reactor every day and has likely reached its maximum capacity. WWTP HLD 1 “c” however receives a load of about 7 kg/(m³*d) resulting in an increase in substrate fed to the second digester leading to the spike in substrate removal.

The adjusted single rate design kinetic models presented in this chapter show, that the Michaelis-Menten type kinetics presents a better fit to the observed results at lower hydraulic retention times.

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This single rate kinetic approach will allow the design engineer to predict the biogas production and solids removal with higher precision and support optimization of digester design. Given the variation of substrate quality for each individual WWTP, from biodegradability of the sludge to variation in inflow particle size, when possible, experimental checks of the model parameters are recommended. However, the application of the mechanistic principles that rule Michaelis-Menten kinetics increase the possibilities of improving and optimizing digester design.

9.5. DESIGN EXPANSIONS: CSTR WITH RECUPERATIVE THICKENING

Recuperative thickening, or the decoupling of hydraulic retention time and sludge retention time, is a common method of improving biologic processes. The waste activated sludge process is a traditional example. Thickened biomass from the secondary settling tank returns to the reactor as “return activated sludge” and enriches the mixed liquor suspended solids. This results in sludge ages of several days and hydraulic retention times of only a few hours. One of the challenges presented when working with anaerobic sludge is that this sludge does not settle as easily and separation technologies more complex than a settling tank are required.

The successful use of recuperative thickening with rotating disk filters in anaerobic sludge digestion at hydraulic retention times of about 8 days and sludge retention times of about 10 days has been reported

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by Kempter-Regel and Trösch (2009). Bharambe et al. (2015) observed positive effects of recuperative thickening in digesters at hydraulic retention times of about 11.5 days. The increase in the sludge age resulted in increased TVS removal as well as higher biogas production rates. Yang et al. (2015) state that the positive effect of recuperative thickening was only observed when the reference digester was at short HRTs.

Figure 60 and Figure 61 show the effect of recuperative thickening for Michaelis-Menten type kinetics considering the effect of a filter that removes 10 %, 20 % or 30 % of the flow. The blue line presents a reference where hydraulic and sludge retention time are identical, the pink lines show the effect of a decrease in hydraulic retention time while the sludge retention time stays at the reference curve.

Full Scale Anaerobic Digester Performance Prediction through Single Rate Kinetics

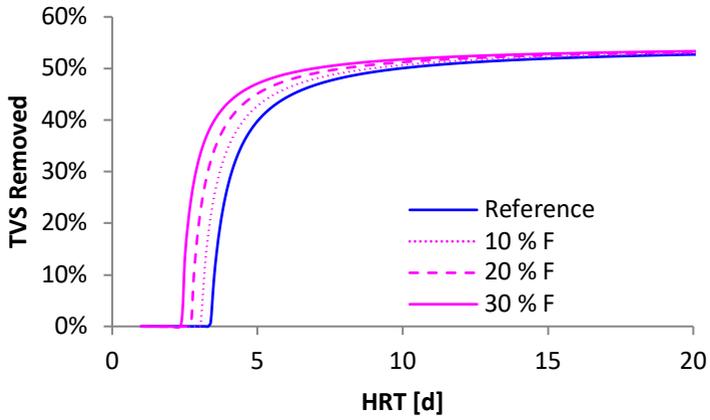


Figure 60: TVS removal with recuperative thickening CSTR with Michaelis-Menten type kinetics C_{TVS0} 40 g/l, C_M 5 g/l, k_{Cmax} 0.36 1/d

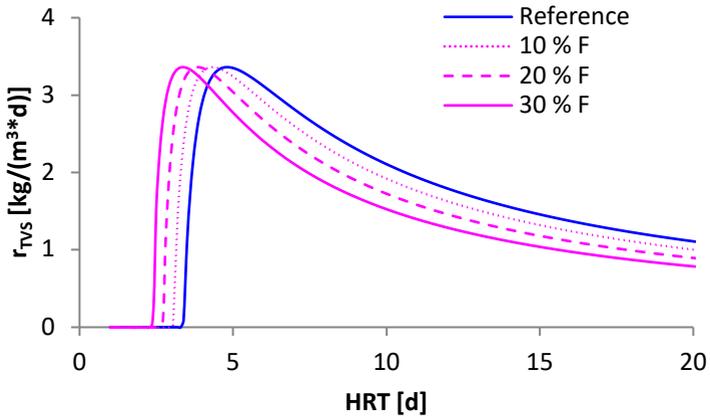


Figure 61: TVS removal rate with recuperative thickening CSTR with Michaelis-Menten type kinetics C_{TVS0} 40 g/l, C_M 5 g/l; k_{Cmax} 0.36 1/d

Full Scale Anaerobic Digester Performance Prediction through Single Rate Kinetics

As observed in literature, the recuperative thickening can have a positive effect on solids removal and reaction rate at lower hydraulic retention times. It reduces the necessary hydraulic retention time in a reactor and shifts the maximum reaction rate, or increases the performance of an existing digester through the increase of biomass concentration. At hydraulic retention times above 20 days under the presented conditions the effect of recuperative thickening is only marginal.

The use of single rate Michaelis-Menten type kinetics seems to predict the effects of recuperative thickening on the reactor performance as described in literature. It predicts performance improvements and washout situations. This sheds a light on how and when to use recuperative thickening, allows the planning engineer to execute a cost analysis for the use of recuperative thickening and select an appropriate thickening technology.

10. CONCLUSION

This thesis evaluated the existing design recommendations and first order kinetic approach to model anaerobic digesters and suggested an expansion of the kinetic model to include Michaelis-Menten type kinetics. It showed that it is reasonable and possible to describe the performance observed in the high load anaerobic digester for the anaerobic digestion of sludge from wastewater treatment plants through single rate Michaelis-Menten type kinetics. It also confirmed that first order kinetics accurately describe conventional anaerobic digesters. Michaelis-Menten type kinetics were especially adequate at lower hydraulic retention times. It described digester performance adequately at various loads.

10.1. WWTP ANALYSIS AND DIGESTER PERFORMANCE

The first aim of this thesis was to identify and characterize the design and operational parameters of existing WWTPs equipped with conventional and high-load anaerobic digesters. This aim was pursued to expand the availability of information on operational data of full-scale digesters. The operational data from four high load anaerobic digesters and eight conventional anaerobic digesters was analyzed. More than 40 years of operational data and 18 distinct operational conditions were identified. The analyzed WWTPs presented a variation of solids concentration at the inflow of the

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anaerobic digester between 2 % TS and 9 % TS and a solids composition influenced by primary and waste activated sludge.

Overall, information on primary sludge is relatively poor or inexistent. Sampling has little standardization and measurements only reflect momentary properties. Thus, it was only possible to use primary sludge values as an auxiliary parameter. Better analysis and sampling methods are necessary to optimize the management of this sludge stream. Higher data quality was obtained regarding WAS. However, there is no significant focus on managing the waste activated sludge to improve anaerobic digestion performance. The most relevant information on sludge quality and quantity originated from the analysis of the raw sludge. Raw sludge characteristics were more readily available, however, even this sludge stream would profit from increased standardization on analysis and sampling, to increase information density and allow action in the optimization of anaerobic digesters.

The analysis of anaerobic digester characteristics showed, that the high load digestion HRTs ranged between 5.1 days and 12 days, and that all HLDs maintain a minimum HRT of about 5 days. The HRT of conventional digesters ranged from 10 to 84 days. The difference in HRTs of the different WWTPs was expected, given that high load digesters are relatively new (the oldest one on a municipal WWTP is from 1994), while regular digesters can be significantly older and prone to historic developments such as oversized population growth

Conclusion

expectancy, unplanned industrial development and safety factors during the design phase. Variation of HRT in any digester did not surpass 10 % between the quartiles and the median. Median organic loading rates of the high load digesters, ranging between 2.7 $\text{kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ to 6.9 $\text{kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$, were significantly higher than from conventional digesters, at 0.3 $\text{kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$ to 2.0 $\text{kg}_{\text{TVS}}/(\text{m}^3 \cdot \text{d})$. The combination of this information covered a wide range of operational parameters, allowing a broad analysis of digester performance.

The digester performance evaluation showed that the evaluated specific biogas production per added volatile solids ranged within literature data, varying between 395 $\text{m}^3/\text{Mg}_{\text{TVS}_{\text{ad}}}$ and 614 $\text{m}^3/\text{Mg}_{\text{TVS}_{\text{ad}}}$. The TVS removal fraction varied between 47 % and 68 %. If normalized, all TVS removal fractions were within or above the recommended 85 % biodegradable TVS removal range. WWTPs with a higher fraction of primary sludge presented a higher TVS removal. Even though the WWTPs with high HRTs presented an effective digestion performance, they did not present higher effectiveness than the standard design anaerobic digester, or digesters operated under high load conditions. The sludge composition, much more than the hydraulic retention time, influenced the digester effectiveness. Furthermore, once reaching maximum decomposition, no further degradation occurred, showing that extremely high hydraulic retention times do not improve digestion performance.

Conclusion

The reaction rate of biogas production varied between 0.15 $\text{m}^3/(\text{m}^3\cdot\text{d})$ and 3.40 $\text{m}^3/(\text{m}^3\cdot\text{d})$, the reaction rate of TVS removal varied between 0.20 $\text{kg}/(\text{m}^3\cdot\text{d})$ and 3.30 $\text{kg}/(\text{m}^3\cdot\text{d})$ and as expected, lower HRTs presented higher reaction rates. It was relevant to observe, that digesters with similar hydraulic retention times presented different reaction rates. Decreasing hydraulic retention times, combined with high total and organic solids concentration at the inflow and improved design conditions resulted in increased digester efficiency.

WWTP HLD 1 presented a particularly interesting case, given its three distinct operational conditions. The inflow TVS concentration was practically constant; however, under different HRTs. Operational condition “b” presented the best digester performance among the three, likely due to its higher primary sludge fraction. Condition “a” followed closely. The evaluation of condition “c” showed that 30 % of the organic load removal occurred in the second reactor. Here it seemed the first reactor was overloaded and the second reactor was able to compensate the overload. This distinction was not easily observable when analyzing digester effectiveness, indicating the relevance of analyzing digester efficiency.

10.2. EFFECT SINGLE RATE KINETICS AND ANAEROBIC DIGESTER DESIGN

The second aim of this thesis was to evaluate the effect of single rate kinetics over anaerobic digester design and analyze its consequences

Conclusion

regarding digester optimization. Here, first order kinetics and Michaelis-Menten type kinetics were compared, based on a range of kinetic constants presented in literature. Advantages, disadvantages, accuracy and mechanistic background of both kinetic models were discussed.

Applying first order kinetics will result in simpler equations and in the compromise that the reaction rate will only be dependent on the substrate concentration. Thus, it is not possible to simulate cell washout. Mathematically, five variables influence first order kinetics: temperature " T ", hydrolysis constant " k_{Hyd} ", inflow biodegradable total volatile solids concentration " C_{bTVS0} ", hydraulic retention time " τ_m " and the recalcitrant fraction " C_R ". Increase of hydraulic retention time, increase in temperature, increase of the hydrolysis constant and multiple reactors systems were identified as methods of choice to improve digester effectiveness. This results in 1) the construction of large digesters, 2) pre-treatment of the incoming sludge, e.g. through thermal hydrolysis, aiming at improving the hydrolysis constant and biodegradability and 3) setting digesters in series to improve efficiency. Given the reaction rate is at its highest at the lowest hydraulic retention time, this type of kinetic might induce to the design of several small digesters in series, which under Michaelis-Menten type kinetics would result in a cell washout. Applying first order kinetics on continuous stirred tank reactors for anaerobic digestion of sludge leads to the conclusion that the solids

Conclusion

stabilization fraction is independent of biomass concentration. This can be misleading.

From a mechanistic point of view, Michaelis-Menten type kinetics present the advantage of describing the combined effect of substrate concentration as well as catalyzer concentration (be it the enzyme or biomass) over the biologic process. Mathematically, five variables influence Michaelis-Menten type kinetics: the Michaelis-Menten type constant C_M , the maximum specific biomass growth rate k_{Cmax} , the inflow biodegradable substrate concentration " C_{bTVS0} ", the hydraulic retention time " τ_m " and the recalcitrant fraction " C_R ", the effect of temperature is implicit in the kinetic constants. This type of kinetic scheme leads to the conclusion that there are four ways to improve digestion efficiency: Increase the hydraulic retention time, increase the specific biomass growth rate " k_C ", decrease the Michaelis-Menten type kinetic constant " C_M " or increase the inflow substrate concentration C_{bTVS0} (or reduce the recalcitrant fraction). This results in 1) the construction of large enough digesters, 2) pre-treatment of the incoming sludge, e.g. through thermal hydrolysis, aiming at improving kinetic constants and biodegradability, 3) thickening inflowing sludge and 4) setting digesters in series to improve efficiency with the limitation of washout conditions.

One interesting aspect of the Michaelis-Menten type model is that in a CSTR in steady state the outflow concentration of substrate will be constant for a particular hydraulic retention time. Consequently, the

Conclusion

TVS removal and biomass growth are influenced by the inflow concentration. Low organic solids concentration at the inflow result in lower biomass production and as a consequence in a significantly slower degradation rate requiring a longer reaction time. The opposite is also true, higher substrate concentration at the inflow will result in higher biomass concentration and faster degradation. Thus, it is possible to affect reactor performance by improving the input material.

Through Michaelis-Menten type kinetics it is possible to demonstrate, that even at low HRTs the technical digestion level of about 85 % biodegradable TVS removal can be reached, while the first order kinetic model would predict about 20 days hydraulic retention time for this performance, unless the k_{1st} values are adjusted.

The analysis for the Michaelis-Menten type kinetic approach with the selected constants showed that among the evaluated parameters a significant effect results from low specific biomass growth rates. Thus, optimal conditions for biomass growth with as little non-competitive inhibitions as possible, such as pH and ammonia toxicity, should be aimed for. The highest positive effect on the other hand, results from high biodegradability. The more biodegradable a substance, more biogas is produced and less solids need to be disposed of. Aiming at increasing substrate biodegradability is one of the more common approaches to improving anaerobic digestion

Conclusion

performance. Design engineers could contribute by preparing or developing measures right from the concept phase to manage potential inhibitions and increase biodegradation.

Nevertheless, it was observed, that both kinetic approaches, first order and Michaelis-Menten type kinetics, result in similar improvement strategies, namely: increasing solids thickening at the inflow, in the first case to increase the hydraulic retention time and in the second case to increase food density for bacterial growth, improving biodegradability of the substrate and influencing the kinetic parameters.

Furthermore, it is essential to be aware of the limitations of this kinetic approach. The quasi steady state assumption identifies the necessary conditions for the application of Michaelis-Menten type kinetics, the *sine qua non* condition expresses that the sum of substrate concentration and the Michaelis-Menten constant need to be significantly higher than the biomass or enzyme concentration. If this is not the case, e.g., if there is an excess of biomass or enzymes, the Michaelis-Menten kinetic model is not valid and should not be applied. Before applying this type of kinetics this hypothesis needs to be tested.

At higher hydraulic retention times, first order kinetics and Michaelis-Menten type kinetics seemed to be interchangeable, while at lower HRTs, this was no longer the case. Under the evaluated conditions, first order kinetics would result in an under estimation of the solids

Conclusion

removal fraction for hydraulic retention times between 6 and 20 days. It would not take into account the washout phenomena, result in an under estimation of the reaction rate for hydraulic retention times between 4 days and 20 days, and an over estimation of the reaction rate for hydraulic retention times below 4 days.

10.3. FULL-SCALE ANAEROBIC DIGESTER PERFORMANCE PREDICTION THROUGH SINGLE RATE KINETICS

The third aim of this thesis was to evaluate the quality of single rate digester design model predictions based on results from full-scale anaerobic digesters operating between 5 and 85 days of hydraulic retention time, focusing on characterizing the operational conditions of the high load anaerobic digester. The data from the analyzed anaerobic digesters were overlapped with the presented kinetic models. These results were fitted to the design recommendations from literature, considering a single rate determining step ruled by first order kinetics; and to the model proposed in this thesis of a single rate determining step ruled by Michaelis-Menten type kinetics. This analysis was executed considering completely mixed reactors, two completely mixed reactors in series and the decoupling of the sludge retention time from the hydraulic retention time, identifying its possibilities and limitations. The presented results showed that a Michaelis-Menten type model could acceptably predict the performance of the high load digestion.

Conclusion

The analysis of full-scale digesters presented challenges, particularly regarding data precision. Full-scale digesters, under operational conditions receive a wide range of sludge quality, turning the prediction of substrate biodegradability especially complex. The wide range of possible primary and waste activated sludge biodegradability values challenges the application of precise models, however, even under operational conditions, median values allowed to demonstrate mechanisms and tendencies.

The use of Michaelis-Menten kinetics described the influence of feed concentration to reactor performance. However, based on the models presented in Chapter 8, this effect is not easily observable when analyzing digester effectiveness, especially considering the measurement precision of total solids and total volatile solids concentrations. It was possible to show, that, under the evaluated range, more relevant information was extracted from the analysis of digester efficiency. It was possible to show, that considering Michaelis-Menten type kinetics, some of the high load digesters were operating close to its maximum reaction rate. The kinetic approach suggests that any small variation of the hydraulic retention time or substrate feed concentration to these digesters would have a significant effect on the reaction rate. To warrant a good performance, a design recommendation in this case would be to assure constant feed properties through proper installations such as equalization tanks. First order kinetics would not describe this condition.

Conclusion

The evaluated single rate design kinetic models also revealed that, for long hydraulic retention times the selected kinetic approach is not particularly relevant. First order kinetics as well as Michaelis-Menten type kinetics will describe the digester appropriately. However, there is no significant advantage to operate digesters at extremely high HRTs. At lower hydraulic retention times, the Michaelis-Menten type kinetics showed a better fit to the observed results. The possibility of considering maximum reaction rates and washout phenomena, combined with a good level of accuracy allowed an expanded understanding of the optimization potential of an anaerobic digester.

The selection of the Michaelis-Menten type model for anaerobic digestion design presents the following consequences:

- 1) It described the relation between substrate and biomass/enzymes, more specifically the ability to predict biomass or enzyme washout. The design engineer needs to be aware of the maximum reaction rates range and prepare for measures if the process reaches this operational condition.
- 2) In order to achieve high performance the inflow concentration of biodegradable material is essential. The guarantee of a specific solids concentration at inflow significantly affects the minimum design HRT. The design engineer needs to assure that high enough solids concentration can be reached under all operational

Conclusion

conditions for the selected HRT. For this, sludge viscosity, density and the possible non-Newtonian fluid characteristics need to be considered.

- 3) At higher biodegradable material concentration, reaction rates increase significantly, affecting the properties of the bulk sludge. The design engineer has to include solutions to manage potential bulking and foaming situations, as well as reactor mixing. Possible solutions would be a larger headspace, tactics to control fluid removal from the reactor, e.g. through a pumping system instead of an overflow, and technology influence mixing energy, to adapt to mixing demands according to fluid properties, while considering cost and operability factors.

The serial operation of digesters has been properly described through the proposed modeling approach. In most cases, it resulted in an increase of 15 % to 20 % of digestion performance for tanks in series of the same size. The model also opens doors to consider the consequences of different digester sizes. The proposed calculations allow characterizing the second digester and its contribution to process stability.

Overall, the fit of both models improves when parameters are adjusted to the specific WWTP and sludge quality. The adjusted Michaelis-Menten type kinetics presented a better fit to the observed results at lower hydraulic retention times compared to first

Conclusion

order kinetics. Allowing the design engineer to predict the biogas production and solids removal with higher precision and support optimization of digester design. Given the variation of substrate quality for each individual WWTP, from biodegradability of the sludge to variation in inflow particle size, when possible, experimental checks of the model parameters are recommended.

The application of single rate Michaelis-Menten type kinetics seems to predict the effects of recuperative thickening on reactor performance as described in literature. It predicts performance improvements, increased process stability and washout situations. This sheds a light on how and when to use recuperative thickening, allows the planning engineer to execute a cost analysis and helps to select an appropriate thickening technology.

Finally, a simple Michaelis-Menten type kinetic model presented a better fit to the observed results, especially at lower hydraulic retention times. This single rate kinetic approach allows the design engineer to predict the biogas production and solids removal with higher precision and supports optimization of digester design. The application of the mechanistic principles that rule Michaelis-Menten kinetics increase the possibilities of improving digester design. When planning a new digestion system or when troubleshooting at a wastewater treatment plant, this approach presents tools to accurately describe the biogas production and identify which

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parameters need to be adapted for an improved sludge management.

11. OUTLOOK

The context of a circular economy is turning the WWTP sludge into a product and no longer looking at it as waste to be disposed of. To turn this context into a more palpable reality, and actually transform sludge from water reclamation facilities into a product, further steps are needed.

The first step is to improve data quality. Not all water reclamation facilities measure the total solids and total volatile solids concentrations fed to their anaerobic digesters. Those that measure it usually only collect single samples throughout the day, and ultimately, the information “volatile solids concentration” is relatively inaccurate. If sludge is to be a usable product, more and better measurements need to be implemented. Solids sampling should be much more consistent and measurements of the solid phase should be expanded to improve mass balancing and modeling.

In Germany, COD measurement for sludge is under consideration. A comparative measurement within the scope of the cross-sectoral theme “sewage sludge” funded by the Federal German Ministry of Education and Research (BMBF) evaluated several COD measuring methods and observed that all measurement procedures were consistent and appropriate to be used in the mass balance of anaerobic digesters (SCHAUM et al., 2016). Separate and systematic sampling of primary and waste activated sludge, also measuring COD,

Outlook

will likely improve the insight on sludge quality and improve predictability of the presented model. In addition, COD loads to the digester might allow a deeper insight to the biogas output.

Further research and application of sludge pre-treatment to increase biodegradability, as well as reactor design, regarding reactor sizes, mixing and recuperative thickening should be aimed at. Especially considering the different types of organic waste and sludge produced by society. It was observed that several of the analyzed anaerobic digesters in this work were oversized. This presents the opportunity of combining anaerobic digestion of sludge and other substrates, e.g. municipal or industrial organic waste, in the existing underutilized infrastructure. Legal limitations such as the separate treatment of sludge and organic waste should be revisited to allow a more integrated solution.

The challenging task to expand CFD models to include the solid and gas phase to simulate digester design might be necessary to improve digester mixing, especially under high load and short hydraulic retention time conditions. Including segregation levels to the digester design and adding the behavior of non-ideal reactors are also necessary steps to improve overall anaerobic digestion processes and model predictions.

Irrespective of its complexity, be it single rate kinetics or the multi-step anaerobic digestion models such as the ADM1, most models for anaerobic digestion focus on the description of this complex process

Outlook

chain. With improved precision of measurement, a next step towards digitalization and circular economy would be to apply these models, not only in the design of anaerobic digesters, but also on the operation of these systems. Allowing the use of models to improve process control and allow feedback loops to improve the operation on the water reclamation facility as a whole.

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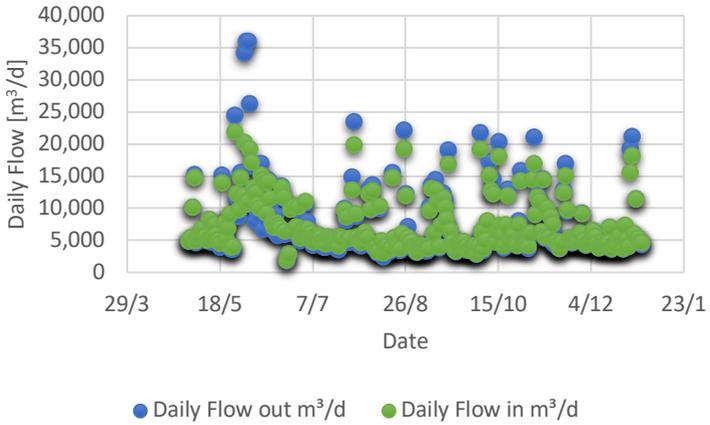
Annex

13. ANNEX

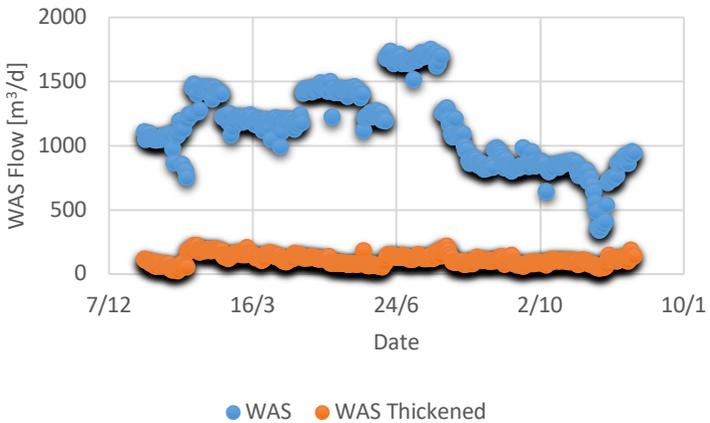
13.1. EXCERPT OF RAW DATA FROM OPERATIONAL DATA BOOK

Datum	Typ	Allgemeines				Rechen und Saniffrang										Zustauf VRB									
		Auslaßtemperatur	Auslaßtemperatur Minimum	Wasser	Neberichtig	Gesamtauf	Gesamtauf	Gesamtauf	Flächenwärme-Einleider	Trockenwärme-Zulauf	Speisepumpe	Minim	Maxim	pH-Wert	pH-Wert Minimum	Rechenputz	Seel	Menge	Menge Zulauf	Flächenwärme-Einleider	CEB	N-Gehalt	Phosphat	SKM (CEB)	SKM (UE)
		°C	°C	mm		kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h
01.03.2013	Fr	5.4	1.8	1	0.0	12.460	12.460	460	12.460	291	7.8	8.2					10.000	12.610						298	46.2
02.03.2013	Sa	2.5	5.6	1	0.0	11.000	11.000	460	11.000	719	7.9	8.2					12.900	12.430						254	38.9
03.03.2013	So	4.9	7.4	1	0.0	11.000	11.000	460	11.000	568	7.9	8.3					12.530	12.500						258	46.1
04.03.2013	Mo	4.2	11.9	1	0.0	11.000	11.000	470	11.000	617	7.9	8.3					12.510	12.500						270	44.1
05.03.2013	Di	5.3	15.8	1	0.0	11.230	11.230	460	11.230	733	7.8	8.3					12.810	12.360	372	43	5.5			295	40.3
06.03.2013	Mi	1.9	16.8	1	0.0	11.740	11.740	460	11.740	758	7.9	8.3					13.150	12.610						270	36.1
07.03.2013	Do	3.2	20.0	1	0.0	12.210	12.210	460	12.210	863	7.9	8.3					13.260	12.860						287	36.5
08.03.2013	Fr	2.6	20.7	1	0.0	12.280	12.280	475	12.280	794	7.8	8.2					13.560	13.104						276	49.8
09.03.2013	Sa	4.3	16.4	3	0.8	18.180		460		1.568	7.8	8.2					17.450	16.910						280	55.2
10.03.2013	So	2.0	11.6	7	0.0	12.680		460		778	7.8	8.3					13.220	12.740						248	56.3
11.03.2013	Mo	1.1	2.8	3	2.2	17.460		460		1.901	7.8	8.3	2.00				18.110	17.630	383	34	4.8			235	46.9
12.03.2013	Di	-2.3	3.1	3	1.5	15.200		460		1.263	7.8	8.6					16.300	15.620						218	72.8
13.03.2013	Mi	-7.0	-7.8	2	0.0	12.320	12.320	460	12.320	752	8.9	8.3					13.180	12.660						217	70.8
14.03.2013	Do	4.8	13.7	1	0.0	12.110	12.110	460	12.110	661	8.0	8.3					13.550	13.010						228	52.4
15.03.2013	Fr	5.8	2.2	2	0.0	11.000	11.000	468	11.000	681	7.8	8.3					12.600	12.411						247	27.5
16.03.2013	Sa	6.0	6.1	1	0.0	11.360	11.360	460	11.360	720	7.9	8.3					11.860	11.600						280	19.2
17.03.2013	So	6.8	6.1	3	3.2	20.560		460		2.448	7.7	8.3					19.620	19.140						264	34.4
18.03.2013	Mo	5.3	5.7	3	5.3	20.960		460		2.197	7.7	8.2					20.900	20.510						247	15.5
19.03.2013	Di	0.6	6.6	3	0.5	18.960		460		1.819	7.8	8.4					17.820	17.360	287	33	4.2			184	21.5
20.03.2013	Mi	0.8	8.7	3	0.8	14.460		477		928	7.9	8.3					14.860	14.380						210	16.3
21.03.2013	Do	1.8	7.7	7	0.0	14.860		460		1.995	7.7	8.3	2.00				15.340	14.860						203	19.5
22.03.2013	Fr	4.2	10.0	2	0.0	11.840	11.840	460	11.840	709	7.9	8.3					12.760	12.280						248	16.2
23.03.2013	Sa	5.2	3.1	3	1.3	15.210		460		1.369	7.8	8.3					15.720	15.250						236	14.7
24.03.2013	So	5.8	4.8	1	0.0	12.600	12.600	460	12.600	601	8.0	8.3					13.020	13.420						228	14.5
25.03.2013	Mo	3.0	0.6	6	3.4	17.080		460		1.184	7.8	8.3					16.460	16.010	305	52	4.1			214	6.8
26.03.2013	Di	6.4	0.5	6	0.5	14.810		460		1.048	7.9	8.3					16.040	15.560						212	10.0
27.03.2013	Mi	8.0	1.9	7	0.0	16.760		460		1.081	7.8	8.3					15.500	14.820						198	6.4
28.03.2013	Do	5.5	7.1	3	1.0	16.760		460		1.798	7.8	8.3					15.920	16.420						261	7.8
29.03.2013	Fr	1.7	6.7	7	0.06	15.260		460		961	7.8	8.3					16.740	16.260						251	11.3
30.03.2013	Sa	-2.8	6.6	7	0.0	12.460		460		799	8.0	8.3					13.020	13.160						211	8.3
31.03.2013	So	0.2	4.6	1	0.0	11.680	11.680	460	11.680	719	8.0	8.3					12.360	11.860						232	8.8
01.04.2013	Mo	4.4	6.0	1	0.0	11.420	11.420	460	11.420	704	8.0	8.3					12.750	12.270						244	8.6
02.04.2013	Di	-7.1	4.7	1	0.0	12.160	12.160	460	12.160	808	8.06	8.3					12.750	12.250	459	46	4.4			207	26.7

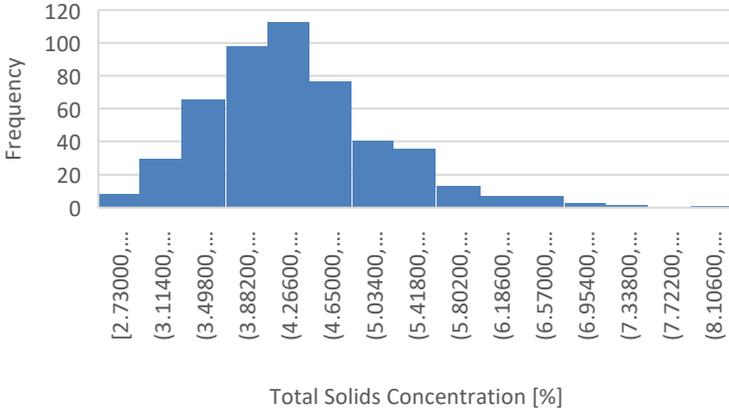
13.2. EXAMPLE INFLOW WWTP



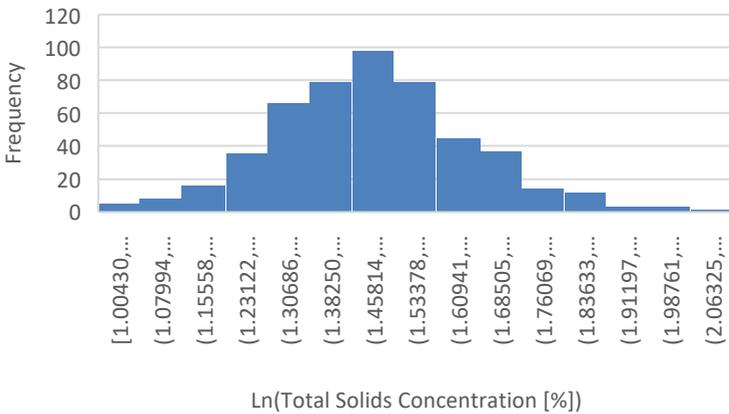
13.3. EXAMPLE WAS FLOW



13.4. EXAMPLE LOG NORMAL DISTRIBUTION AND OUTLIER IDENTIFICATION



EXAMPLE OF HISTOGRAM FOR TOTAL SOLIDS CONCENTRATION (N = 501)



EXAMPLE OF HISTOGRAM FOR THE NATURAL LOGARITHM OF THE TOTAL SOLIDS CONCENTRATION (N=501)

Annex

EXAMPLE OF THE DETERMINATION OF UPPER AND LOWER OUTLIER LIMITS FOR NORMAL AND LOG NORMAL DISTRIBUTION

	Normal Distribution		Log Normal Distribution	
Mean	\bar{x}	4,52	\bar{x}^*	4,45
Standard Deviation	s	0,82	s^*	1,19
Upper outlier limit	$x + 3*s$	6,98	$x^* * s^{*3}$	7,52
Lower outlier limit	$x - 3*s$	2,07	x^* / s^{*3}	2,63

13.5. FURTHER ANALYSIS SUBSTRATE QUALITY

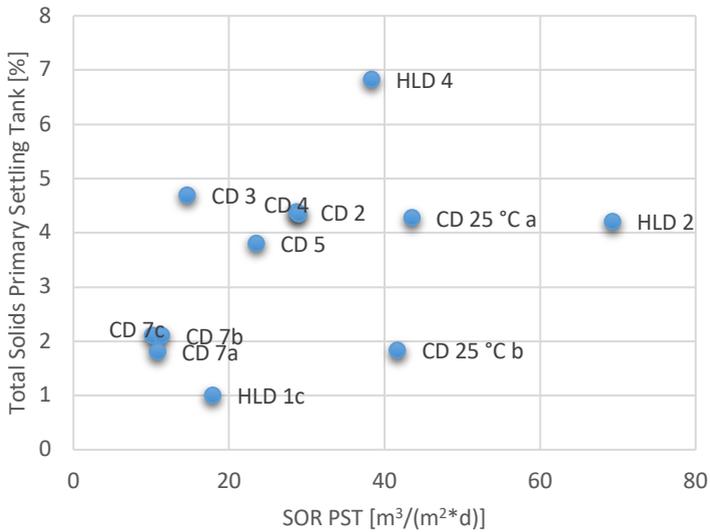


FIGURE ANNEX 1: CORRELATION BETWEEN MEDIAN TOTAL SOLIDS CONCENTRATION AND SURFACE OVERFLOW RATE OF THE PRIMARY SETTLING TANK

Annex

It was not possible to establish a definite correlation between the total solids concentration in the primary settling tank and the surface overflow rate. The primary sludge removal technique plays a significant role in the sludge thickness. This is due to the primary settling tank design and sludge removal strategy. E. g. WWTP HLD 1 has a SOR of $18 \text{ m}^3/(\text{m}^2 \cdot \text{d})$, however the total solids content registered in the primary sludge is at 1 % – 2 % in mass. Even though the PST is equipped with a thickener, no particular attention is set to remove a thick sludge fraction, given that this WWTP thickens the combined primary and waste activated sludge mechanically, and primary sludge solids content is not relevant. WWTP CD 7 has a very low SOR of $10 \text{ m}^3/(\text{m}^2 \cdot \text{d})$ and pumps a relatively thin sludge out of the primary settling tank. The sludge is further thickened in static pre-thickening tank together with the WAS before being pumped into the digester. On the other side of the primary sludge-thickening spectrum lies WWTP CD 2. It removes the primary sludge from the thickening conus according to a sludge-blanket level sensor guaranteeing a relatively thick and homogeneous primary sludge fraction at a median value of 4.4 % in mass.

Annex

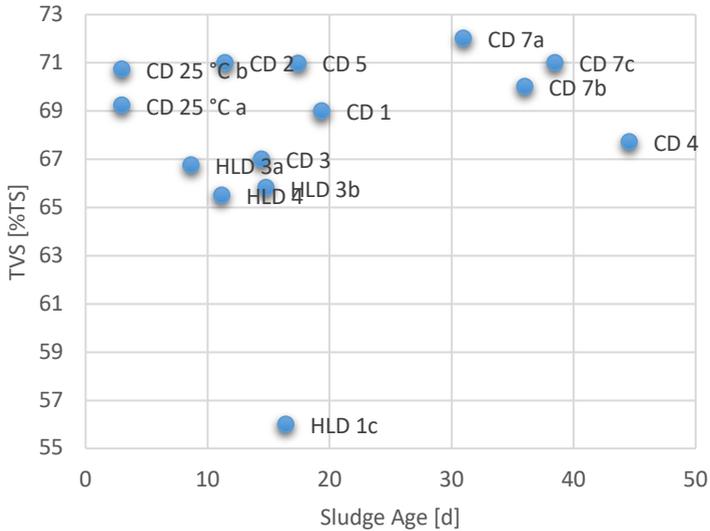


FIGURE ANNEX 2: CORRELATION BETWEEN LOSS OF IGNITION AND SLUDGE AGE FOR WASTE ACTIVATED SLUDGE

WWTP CD 25 °C, with the shortest sludge age, presented a TVS of 70 %, however the TVS of WWTP CD 2 with a sludge age of 11 days and of WWTP CD 7 with a sludge age of over 30 days also presented a TVS of about 70 %. The values were mostly within the typical range. It was not possible to establish a definite correlation between the loss of ignition of the waste activated sludge and the sludge age. The biodegradability of the WAS, and not its loss of ignition are likely to be the relevant parameters for correlation, as presented by (Gossett and Belser 1982).

13.6. ANALYSIS ANOVA

TABLE ANNEX 1: ONE-WAY ANOVA ANALYSIS HLD 1

Summary				
<i>Groups</i>	<i>Obs.</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
HLD 1c	499	2698.62	5.41	0.61
HLD 1b	360	2252.34	6.26	1.27
HLD 1a	1449	10108.06	6.98	0.91

ANOVA						
<i>Source of Variation</i>	<i>Sums of Squares (SS)</i>	<i>Degrees of freedom (df)</i>	<i>Mean Square (MS)</i>	<i>F-Value</i>	<i>P-Value</i>	<i>Critical F-Value</i>
Difference Between groups	943.06	2	471.53	524.11	$2.42 * 10^{-188}$	3.00
Within the group	2073.77	2305	0.90			
Total	3016.83	2307				

Annex

TABLE ANNEX 2: ONE-WAY ANOVA ANALYSIS HLD 3

Summary						
Groups	<i>Obs.</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>		
HLD 3a	1007	6081.70	6.04	1.14		
HLD 3b	242	1684.94	6.96	1.19		

ANOVA						
Source of Variation	<i>Sums of Squares (SS)</i>	<i>Degrees of freedom (df)</i>	<i>Mean Square (MS)</i>	<i>F-Value</i>	<i>P-Value</i>	<i>Critical F-Value</i>
Difference Between groups	166.27	1	166.27	144.47	1.44×10^{-31}	3.85
Within the group	1435.11	1247	1.15			
Total	1601.38	1248				

Annex

TABLE ANNEX 3: ONE-WAY ANOVA ANALYSIS CD 25 °C

Summary						
<i>Groups</i>	<i>Obs.</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>		
CD 25 °C b	658	7111.54	10.81	2.79		
CD 25 °C a	317	5955.16	18.79	2.26		
ANOVA						
<i>Source of Variation</i>	<i>Sums of Squares (SS)</i>	<i>Degrees of freedom (df)</i>	<i>Mean Square (MS)</i>	<i>F-Value</i>	<i>P-Value</i>	<i>Critical F-Value</i>
Difference Between groups	13617.23	1	13617.23	5199.30	0	3.85
Within the group	2548.34	973	2.62			
Total	16165.57	974				

Annex

TABLE ANNEX 4: ONE-WAY ANOVA ANALYSIS CD 7

Summary						
Groups	<i>Obs.</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>		
CD 7c	14	928.59	66.33	2.41		
CD 7a	7	513.99	73.43	2.88		
CD 7b	15	1274.09	84.94	25.51		
ANOVA						
Source of Variation	<i>Sums of Squares (SS)</i>	<i>Degrees of freedom (df)</i>	<i>Mean Square (MS)</i>	<i>F-Value</i>	<i>P-Value</i>	<i>Critical F-Value</i>
Difference Between groups	2544.35	2	1272.18	103.49	6.06*10 ⁻¹⁵	3.28
Within the group	405.68	33	12.29			
Total	2950.03	35				

13.7. TOTAL SOLIDS REMOVAL RATE

13.7.1. CH. 7.2.2

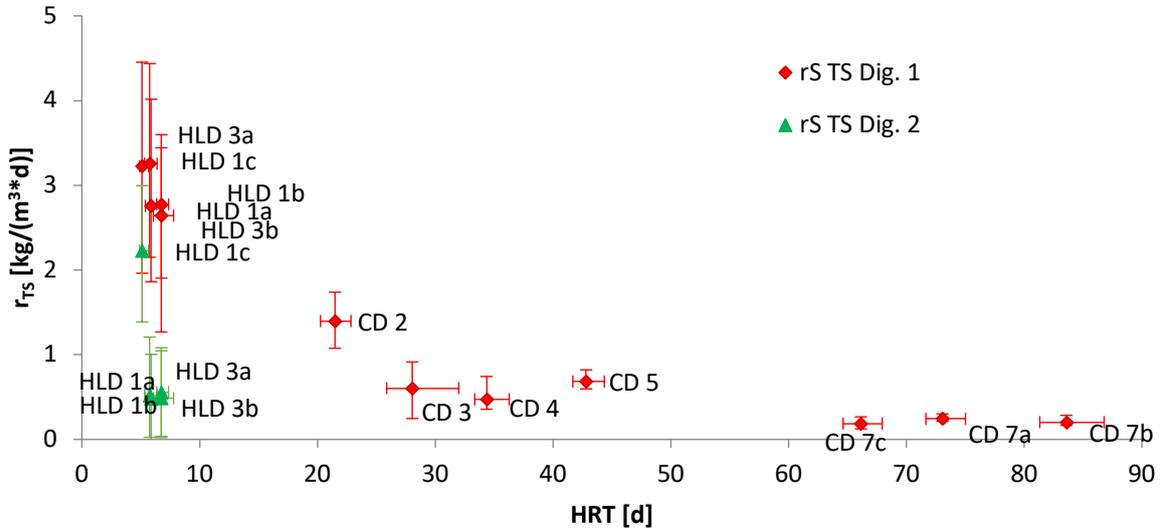


FIGURE ANNEX 3: Substrate removal rates in the first and second digester considering TS measurements

13.7.2. CH. 9.2.2

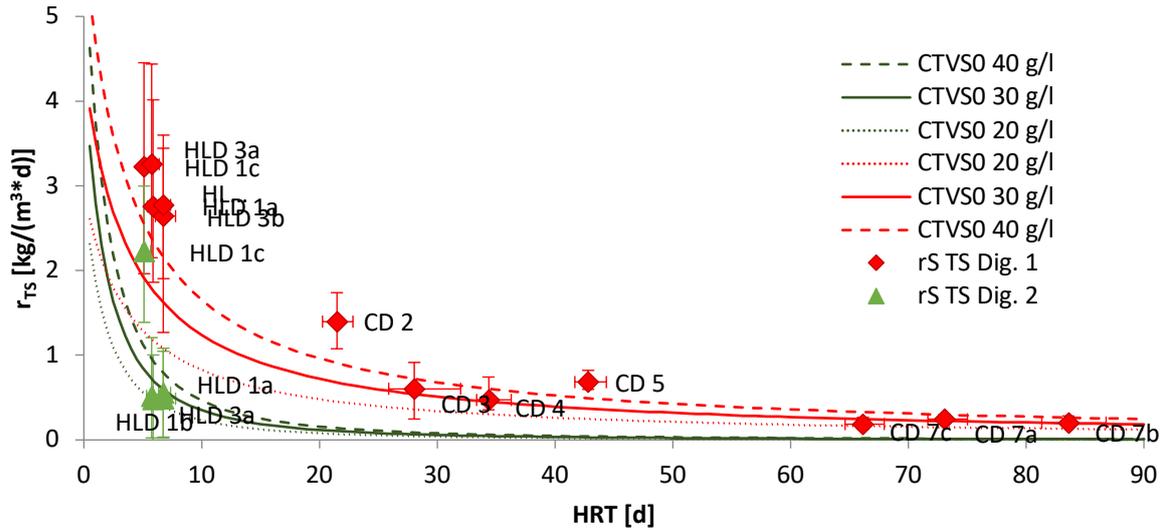


FIGURE ANNEX 4:

Annex

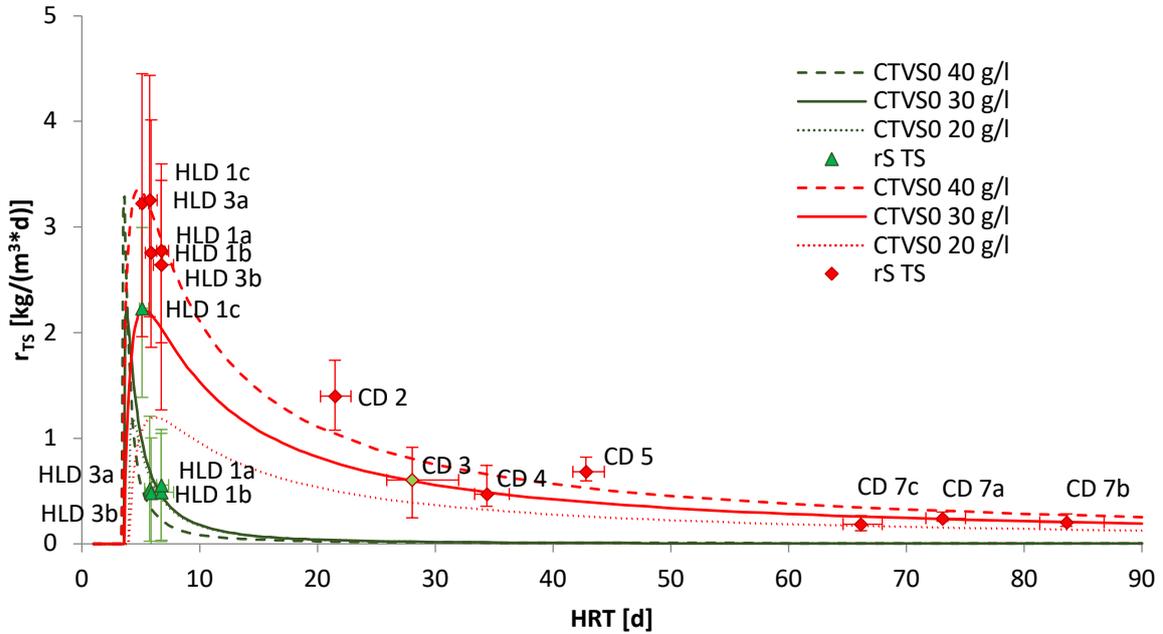


FIGURE ANNEX 5

13.8. ORIGINAL VALUES CH. 6

PRIMARY SLUDGE

TABLE ANNEX 5: SURFACE OVERFLOW RATE

m ³ /(m ² *d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	21.55	11.31	14.97	17.97	22.91	28.41	79.56
HLD 2	78.65	46.29	61.94	69.38	90.54	104.61	165.98
HLD 3a	34.37	1.73	16.50	24.05	42.47	57.99	155.82
HLD 1b							
HLD 3b	35.12	7.96	20.31	25.33	42.67	58.74	163.39
HLD 1a							
HLD 4	49.78	28.03	34.03	38.37	52.87	75.34	124.20
CD 25 °C b	42.34	0.10	38.99	41.72	44.84	47.11	76.77
CD 25 °C a	44.21	32.08	39.27	43.55	46.88	49.51	76.16
CD 1	42.56	18.58	26.96	32.12	48.47	60.58	156.01
CD 2	30.53	22.07	25.73	28.71	34.69	38.66	45.12
CD 3	17.71	0.26	12.71	14.67	19.87	25.88	71.65
CD 4	39.02	24.86	27.61	29.01	34.87	40.07	88.92
CD 5	25.01	13.12	18.82	23.55	27.78	34.27	52.35
CD 6	7.79	0.41	5.02	5.99	8.90	12.74	24.30
CD 7c	10.47	8.78	9.65	10.22	10.97	12.10	12.95
CD 7a	11.38	10.14	10.50	10.86	12.00	12.46	13.14
CD 7b	11.73	8.63	10.05	11.36	13.11	14.35	15.49

Annex

TABLE ANNEX 6: TOTAL SOLIDS IN PRIMARY SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c	1.57	0.20	0.70	1.00	2.10	3.31	5.90
HLD 2	4.22	2.60	3.70	4.20	4.64	5.00	7.10
HLD 3a							
HLD 1b	2.12	0.20	0.93	1.70	3.20	3.60	6.10
HLD 3b							
HLD 1a	1.63	0.20	0.80	1.20	2.20	2.90	5.90
HLD 4	6.74	4.02	5.56	6.82	7.98	8.53	10.22
CD 25 °C b	2.12	1.11	1.55	1.83	2.44	2.87	4.73
CD 25 °C a	4.34	2.29	3.66	4.26	5.08	5.48	7.14
CD 1							
CD 2	4.50	0.36	3.98	4.38	5.04	5.46	8.15
CD 3	4.82	2.30	3.93	4.69	5.33	5.74	15.61
CD 4	4.45	0.35	3.94	4.34	5.00	5.41	8.07
CD 5	3.80	2.80	3.11	3.80	4.25	4.50	5.10
CD 6							
CD 7c	2.05	1.30	1.63	2.10	2.40	2.41	3.30
CD 7a	1.81	1.60	1.75	1.80	1.90	2.00	2.00
CD 7b	2.05	1.40	1.80	2.10	2.25	2.39	2.60

Annex

TABLE ANNEX 7: TOTAL VOLATILE SOLIDS IN PRIMARY SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c							
HLD 2							
HLD 3a							
HLD 1b							
HLD 3b							
HLD 1a							
HLD 4	4.27	3.06	3.62	4.26	4.74	5.25	5.90
CD 25 °C b	1.22	0.76	1.02	1.18	1.35	1.50	3.10
CD 25 °C a	2.49	1.48	2.20	2.58	2.85	2.99	3.38
CD 1							
CD 2	3.22	0.30	2.60	3.25	3.64	3.86	6.25
CD 3	3.47	1.56	2.86	3.30	3.98	4.24	8.17
CD 4	3.52	0.20	3.07	3.43	4.05	4.39	6.73
CD 5	2.99	2.40	2.53	3.12	3.38	3.42	3.48
CD 6							
CD 7c	1.63	1.08	1.33	1.69	1.85	1.89	2.53
CD 7a	1.46	1.28	1.40	1.42	1.53	1.59	1.63
CD 7b	1.62	1.20	1.40	1.65	1.79	1.84	2.17

Annex

TABLE ANNEX 8: TOTAL VOLATILE SOLIDS IN PRIMARY SLUDGE AS % OF TOTAL SOLIDS

%_{TS}	Average	Min	25%	50%	75%	85%	Max
HLD 1c							
HLD 2							
HLD 3a							
HLD 1b							
HLD 3b							
HLD 1a							
HLD 4	65	52	58	65	71	75	80
CD 25 °C b	61	33	53	65	70	71	75
CD 25 °C a	59	28	53	62	67	69	74
CD 1							
CD 2	80	74	78	81	82	84	85
CD 3	73	55	70	73	76	77	85
CD 4	78	55	77	81	83	84	87
CD 5	80	68	79	81	83	84	86
CD 6							
CD 7c	80	77	78	81	82	83	85
CD 7a	80	79	79	80	82	82	82
CD 7b	80	76	78	81	82	82	86

Annex

WASTE ACTIVATED SLUDGE

TABLE ANNEX 9: SLUDGE AGE

d	Average	Min	25%	50%	75%	85%	Max
HLD 1c	15.99	7.38	13.92	16.44	17.77	19.65	24.11
HLD 2							
HLD 3a	11.24	2.23	6.52	8.66	12.25	15.38	74.67
HLD 1b							
HLD 3b	24.53	6.51	10.82	14.79	29.96	46.36	85.59
HLD 1a							
HLD 4	13.79	7.67	9.60	11.18	16.60	18.95	26.75
CD 25 °C b	3.30	2.80	3.00	3.00	3.50	3.50	5.00
CD 25 °C a	3.30	3.00	3.00	3.00	3.50	4.00	4.00
CD 1	24.21	5.82	13.37	19.40	29.34	36.57	92.80
CD 2	11.52	8.88	10.83	11.47	12.22	12.77	14.48
CD 3	17.63	7.50	11.55	14.46	18.32	19.64	85.78
CD 4	41.39	16.03	37.10	44.57	46.87	47.29	49.17
CD 5	18.22	12.87	15.78	17.44	22.72	23.10	23.60
CD 6	36.19	16.95	27.79	34.51	41.23	45.63	98.01
CD 7c	40.14	32.00	35.25	38.50	45.00	48.10	51.00
CD 7a	31.86	26.00	29.50	31.00	32.00	33.10	43.00
CD 7b	37.80	30.00	33.50	36.00	41.00	46.50	49.00

Annex

TABLE ANNEX 10: TOTAL SOLIDS IN WASTE ACTIVATED SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c	0.62	0.49	0.56	0.62	0.66	0.69	1.02
HLD 2	6.75	5.00	6.10	6.70	7.30	7.60	8.80
HLD 3a	7.40	4.10	6.80	7.30	7.98	8.40	12.70
HLD 1b	0.52	0.36	0.48	0.50	0.56	0.61	0.70
HLD 3b	8.04	5.60	7.30	7.70	8.80	9.58	10.30
HLD 1a	0.74	0.15	0.62	0.71	0.83	0.92	1.29
HLD 4	7.41	5.56	6.83	7.33	8.05	8.21	9.20
CD 25 °C b	1.90	1.12	1.66	1.92	2.07	2.24	3.00
CD 25 °C a	2.45	1.57	2.06	2.24	2.60	2.96	8.11
CD 1	5.79	3.40	5.30	5.70	6.20	6.40	8.20
CD 2	7.15	6.80	7.03	7.20	7.28	7.30	7.40
CD 3	6.67	1.52	5.34	6.74	7.71	8.69	10.74
CD 4	5.39	4.64	5.18	5.37	5.57	5.67	6.86
CD 5	4.60	4.60	4.60	4.60	4.60	4.60	4.60
CD 6							
CD 7c	0.56	0.49	0.53	0.55	0.60	0.62	0.68
CD 7a	0.48	0.42	0.46	0.50	0.51	0.51	0.54
CD 7b	0.55	0.42	0.51	0.54	0.60	0.62	0.71

Annex

TABLE ANNEX 11: TOTAL VOLATILE SOLIDS IN WASTE ACTIVATED SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c	0.35	0.26	0.33	0.36	0.37	0.39	0.46
HLD 2							
HLD 3a	4.97	1.93	4.48	4.84	5.27	5.54	10.23
HLD 1b							
HLD 3b	5.33	3.52	4.59	5.05	6.16	6.39	8.35
HLD 1a							
HLD 4	5.09	3.84	4.76	5.06	5.46	5.59	6.30
CD 25 °C b	1.36	0.80	1.22	1.39	1.51	1.57	1.90
CD 25 °C a	1.57	0.82	1.30	1.55	1.70	1.80	7.30
CD 1							
CD 2	4.90	4.22	4.65	5.00	5.13	5.21	5.40
CD 3	4.55	1.00	3.86	4.60	5.23	5.79	7.52
CD 4	3.74	2.27	3.42	3.69	3.88	3.99	6.10
CD 5	3.22	2.85	3.13	3.35	3.36	3.36	3.36
CD 6							
CD 7c	0.40	0.35	0.37	0.39	0.42	0.45	0.47
CD 7a	0.34	0.29	0.32	0.36	0.37	0.37	0.38
CD 7b	0.38	0.28	0.36	0.38	0.40	0.44	0.50

Annex

TABLE ANNEX 12: TOTAL VOLATILE SOLIDS IN WASTE ACTIVATED SLUDGE AS % OF TOTAL SOLIDS

%_{TS}	Average	Min	25%	50%	75%	85%	Max
HLD 1c	55.24	44.00	51.50	56.00	59.00	60.00	63.00
HLD 2							
HLD 3a	66.27	47.01	63.45	66.75	69.63	71.31	80.30
HLD 1b							
HLD 3b	65.74	55.90	62.85	65.80	69.01	70.19	72.80
HLD 1a							
HLD 4	64.81	55.00	64.00	65.50	67.00	68.30	70.50
CD 25 °C b	69.16	48.27	64.65	70.71	74.49	75.60	78.98
CD 25 °C a	65.10	37.78	58.31	69.22	74.06	75.91	89.98
CD 1	68.38	63.00	68.00	69.00	69.00	70.00	72.00
CD 2	70.27	65.10	68.95	71.00	71.85	72.00	72.00
CD 3	66.33	58.00	65.00	67.00	68.00	69.00	73.00
CD 4	68.04	62.50	65.55	67.71	70.05	71.40	77.30
CD 5	69.88	62.00	68.00	70.97	72.97	73.09	73.10
CD 6							
CD 7c	70.64	66.00	70.25	71.00	71.00	72.00	73.00
CD 7a	71.00	69.00	70.00	72.00	72.00	72.00	72.00
CD 7b	69.27	65.00	67.00	70.00	71.00	71.90	73.00

Annex

RAW SLUDGE

TABLE ANNEX 13: TOTAL SOLIDS RAW SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c	4.91	1.80	4.60	5.10	5.50	5.70	6.50
HLD 2	4.92	2.70	4.30	5.00	5.50	5.80	8.00
HLD 3a	5.31	2.90	4.84	5.27	5.69	6.14	7.88
HLD 1b	4.37	2.60	3.80	4.30	4.90	5.20	6.40
HLD 3b	4.92	2.35	4.38	4.92	5.38	5.65	7.65
HLD 1a	5.15	2.10	4.70	5.20	5.70	5.90	6.90
HLD 4	4.35	3.08	3.91	4.27	4.74	4.91	7.72
CD 25 °C b	2.12	1.05	1.65	1.92	2.26	2.62	6.39
CD 25 °C a	3.81	2.68	3.02	3.52	4.38	4.74	6.40
CD 1							
CD 2	5.95	5.00	5.85	6.00	6.30	6.30	7.00
CD 3	5.56	2.74	4.91	5.60	6.22	6.53	8.02
CD 4	4.82	1.36	4.05	4.63	5.55	5.98	10.11
CD 5	4.13	2.62	3.39	4.07	4.80	5.18	5.74
CD 6							
CD 7c	2.66	1.50	2.30	2.50	2.90	3.05	4.00
CD 7a	3.21	2.80	2.95	3.00	3.20	3.41	4.40
CD 7b	3.33	2.50	2.90	3.40	3.60	3.96	4.20

Annex

TABLE ANNEX 14: TOTAL VOLATILE SOLIDS RAW SLUDGE

%_M	Average	Min	25%	50%	75%	85%	Max
HLD 1c	3.50	1.22	3.21	3.59	3.95	4.08	4.75
HLD 2				3.40			
HLD 3a				3.30			
HLD 1b	3.18	1.89	2.69	3.20	3.65	3.81	4.74
HLD 3b				3.09			
HLD 1a	3.64	1.58	3.36	3.71	4.02	4.14	5.18
HLD 4	2.74	2.18	2.56	2.74	2.90	3.02	3.40
CD 25 °C b	1.31	0.74	1.09	1.23	1.38	1.48	4.52
CD 25 °C a	2.13	0.84	1.89	2.10	2.36	2.49	3.24
CD 1							
CD 2	4.40	3.85	4.18	4.45	4.64	4.68	5.11
CD 3	3.97	1.88	3.56	3.97	4.43	4.68	5.51
CD 4	3.64	0.94	3.16	3.54	3.95	4.53	7.30
CD 5	3.02	2.06	2.62	3.04	3.44	3.65	3.95
CD 6							
CD 7c	2.07	1.23	1.76	1.98	2.28	2.35	3.20
CD 7a	2.45	2.04	2.26	2.28	2.46	2.63	3.39
CD 7b	2.57	1.80	2.19	2.64	2.79	3.05	3.23

Annex

TABLE ANNEX 15: TOTAL VOLATILE SOLIDS IN RAW SLUDGE AS % OF TOTAL SOLIDS

%_{TS}	Average	Min	25%	50%	75%	85%	Max
HLD 1c	71.27	54.00	68.00	72.50	75.00	75.55	79.00
HLD 2							
HLD 3a							
HLD 1b	72.83	60.00	70.00	73.00	76.00	77.00	81.00
HLD 3b							
HLD 1a	71.02	55.00	68.00	71.00	75.00	76.00	79.00
HLD 4	58.53	43.80	55.14	60.98	62.13	62.76	69.76
CD 25 °C b	63.77	40.08	56.28	66.30	71.07	72.55	76.05
CD 25 °C a	58.07	29.98	52.64	59.61	67.65	69.19	83.01
CD 1							
CD 2	74.14	68.40	71.90	73.90	77.00	78.00	79.00
CD 3	72.77	50.00	70.00	73.00	76.00	78.00	85.00
CD 4	75.51	56.69	73.59	76.65	78.51	79.13	84.64
CD 5	74.35	68.85	71.86	74.92	77.41	77.94	78.73
CD 6							
CD 7c	77.93	70.00	76.25	78.00	80.00	80.10	82.00
CD 7a	76.14	73.00	75.50	77.00	77.00	77.10	78.00
CD 7b	76.93	72.00	76.00	77.00	78.50	79.00	80.00

Annex

HYDRAULIC RETENTION TIME

TABLE ANNEX 16: HYDRAULIC RETENTION TIME IN DIGESTERS

d	Average	Min	25%	50%	75%	85%	Max
HLD 1c	5.41	4.07	4.94	5.12	5.61	5.88	9.36
HLD 2	5.54	5.38	5.38	5.38	5.38	5.38	7.93
HLD 3a	6.04	4.53	5.38	5.76	6.33	6.89	14.58
HLD 1b	6.26	4.90	5.45	5.89	6.79	7.26	11.65
HLD 3b	6.95	4.81	6.14	6.74	7.72	8.05	11.32
HLD 1a	6.98	5.31	6.42	6.76	7.30	7.63	11.90
HLD 4	10.06	8.57	9.18	10.37	10.60	10.60	11.91
CD 25 °C b	10.81	7.94	9.63	10.50	11.61	12.60	16.05
CD 25 °C a	18.79	15.13	17.76	18.81	20.04	20.56	21.27
CD 1	11.33	3.86	9.71	11.11	11.90	12.66	50.00
CD 2	21.66	18.94	20.48	21.48	22.63	23.29	27.61
CD 3	29.14	21.91	26.17	28.05	31.71	33.80	41.74
CD 4	34.65	31.23	33.69	34.36	35.94	36.27	36.93
CD 5	43.03	41.03	42.12	42.81	43.93	44.44	45.77
CD 6	47.34	34.01	44.73	47.47	50.38	52.42	57.81
CD 7c	66.33	63.86	65.29	66.15	67.29	67.73	69.76
CD 7a	73.43	71.25	72.39	73.06	74.29	74.73	76.32
CD 7b	84.94	79.41	82.16	83.59	85.95	88.14	98.84

Annex

LOADING RATE

TABLE ANNEX 17: SLUDGE LOADING RATE ANAEROBIC DIGESTER 1

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	9.34	2.65	7.98	9.59	10.93	11.45	13.30
HLD 2	9.26	4.12	8.11	9.46	10.52	11.06	15.45
HLD 3a	9.08	2.68	8.01	9.11	10.14	10.79	14.23
HLD 1b	7.09	3.45	6.26	7.18	7.84	8.27	11.12
HLD 3b	7.62	3.00	6.43	7.97	8.53	9.03	12.66
HLD 1a	7.63	3.16	6.75	7.58	8.53	9.07	11.43
HLD 4	5.26	3.43	4.72	5.10	5.76	5.99	7.69
CD 25 °C b	2.03	0.81	1.71	1.96	2.26	2.68	3.62
CD 25 °C a	2.29	1.68	1.93	2.08	2.61	2.77	3.71
CD 1							
CD 2	1.82	1.39	1.66	1.83	1.99	2.11	2.27
CD 3	1.75	0.86	1.49	1.73	1.96	2.11	3.11
CD 4	1.45	0.72	1.26	1.37	1.60	1.68	2.36
CD 5	1.25	1.17	1.19	1.21	1.27	1.32	1.40
CD 6							
CD 7c	0.42	0.24	0.36	0.40	0.45	0.49	0.63
CD 7a	0.46	0.38	0.43	0.43	0.45	0.48	0.61
CD 7b	0.41	0.31	0.36	0.42	0.44	0.46	0.50

Annex

TABLE ANNEX 18: ORGANIC LOADING RATE ANAEROBIC DIGESTER 1

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	6.67	1.80	5.71	6.89	7.81	8.19	9.71
HLD 2				6.43			
HLD 3a							
HLD 1b	5.15	2.41	4.46	5.15	5.76	6.05	7.75
HLD 3b							
HLD 1a	5.39	2.37	4.89	5.42	5.99	6.27	8.00
HLD 4	3.05	2.17	2.75	3.01	3.41	3.55	3.82
CD 25 °C b	1.26	0.56	1.13	1.26	1.38	1.47	1.90
CD 25 °C a	1.31	0.81	1.24	1.28	1.40	1.45	2.80
CD 1							
CD 2	2.02	1.60	1.86	2.02	2.18	2.28	2.37
CD 3	1.26	0.73	1.09	1.26	1.40	1.47	1.98
CD 4	1.09	0.45	0.95	1.05	1.23	1.27	1.93
CD 5	0.91	0.89	0.90	0.92	0.92	0.92	0.92
CD 6							
CD 7c	0.32	0.20	0.27	0.31	0.35	0.38	0.49
CD 7a	0.35	0.28	0.33	0.33	0.35	0.37	0.47
CD 7b	0.31	0.22	0.28	0.33	0.34	0.36	0.39

13.9. ORIGINAL VALUES CH. 7

DIGESTER EFFECTIVENESS

TABLE ANNEX 19: BIOGAS PRODUCTION IN DIGESTER 1

$I/kg_{TVS_{ad}}$	Average	Min	25%	50%	75%	85%	Max
HLD 1c							
HLD 2							
HLD 3a							
HLD 1b							
HLD 3b							
HLD 1a							
HLD 4	519	401	487	512	534	582	647
CD 25 °C b	218	118	168	210	246	288	421
CD 25 °C a	300	171	256	290	322	355	576
CD 1							
CD 2	522	426	493	509	554	566	632
CD 3	734	118	567	732	906	1022	1659
CD 4	577	183	489	535	615	707	1395
CD 5	362	293	338	362	386	405	433
CD 6							
CD 7c	482	288	436	497	543	567	729
CD 7a	467	328	452	504	511	513	514
CD 7b	500	392	420	496	555	607	657

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TABLE ANNEX 20: BIOGAS PRODUCTION IN DIGESTER 1+2

I/kg_{TVS_{ad}}	Average	Min	25%	50%	75%	85%	Max
HLD 1c	407	185	354	395	450	495	717
HLD 2							
HLD 3a							
HLD 1b	430	224	357	422	489	537	724
HLD 3b							
HLD 1a	463	124	409	454	511	543	1061
HLD 4	615	477	570	614	629	692	752
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

TABLE ANNEX 21: TOTAL VOLATILE SOLIDS REMOVED IN DIGESTER 1

	Average	Min	25%	50%	75%	85%	Max
HLD 1c	45%	6%	40%	47%	51%	53%	62%
HLD 2							
HLD 3a							
HLD 1b	49%	21%	44%	51%	57%	59%	67%
HLD 3b							
HLD 1a	48%	3%	44%	49%	54%	56%	70%
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2	62%	53%	59%	64%	65%	66%	67%
CD 3	55%	1%	51%	55%	60%	62%	77%
CD 4	53%	26%	50%	54%	60%	62%	74%
CD 5	52%	48%	51%	53%	54%	54%	55%
CD 6							
CD 7c	61%	46%	53%	62%	66%	67%	81%
CD 7a	68%	57%	66%	68%	72%	73%	74%
CD 7b	66%	57%	61%	66%	70%	71%	74%

Annex

TABLE ANNEX 22: TOTAL VOLATILE SOLIDS REMOVED IN DIGESTER 1+2

	Average	Min	25%	50%	75%	85%	Max
HLD 1c	53%	15%	50%	55%	59%	61%	70%
HLD 2							
HLD 3a							
HLD 1b	57%	17%	51%	58%	64%	65%	78%
HLD 3b							
HLD 1a	57%	15%	53%	58%	62%	64%	73%
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

DIGESTER EFFICIENCY

TABLE ANNEX 23: SPECIFIC BIOGAS PRODUCTION RATE IN REACTOR 1

m³/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c							
HLD 2	3.414	1.779	2.926	3.404	3.868	4.132	5.412
HLD 3a							
HLD 1b							
HLD 3b							
HLD 1a							
HLD 4	1.531	1.094	1.386	1.510	1.673	1.764	1.898
CD 25 °C b	0.270	0.124	0.217	0.262	0.314	0.342	0.503
CD 25 °C a	0.404	0.003	0.363	0.415	0.453	0.486	0.596
CD 1	0.861	0.168	0.767	0.867	0.971	1.022	1.316
CD 2	1.126	0.874	1.043	1.129	1.213	1.225	1.379
CD 3	0.436	0.040	0.360	0.449	0.544	0.582	0.851
CD 4	0.615	0.091	0.549	0.614	0.678	0.722	0.910
CD 5	0.259	0.000	0.180	0.272	0.347	0.384	0.671
CD 6	0.231	0.000	0.202	0.259	0.278	0.288	0.324
CD 7c	0.148	0.113	0.143	0.149	0.155	0.159	0.168
CD 7a	0.159	0.140	0.154	0.162	0.167	0.168	0.168
CD 7b	0.153	0.136	0.145	0.148	0.166	0.170	0.170

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TABLE ANNEX 24: SPECIFIC BIOGAS PRODUCTION RATE IN REACTOR 2

m³/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c							
HLD 2							
HLD 3a							
HLD 1b							
HLD 3b							
HLD 1a							
HLD 4	0.288	0.234	0.262	0.279	0.318	0.329	0.352
CD 25 °C b							
CD 25 °C a							
CD 1	0.111	0.030	0.094	0.105	0.117	0.124	0.853
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

TABLE ANNEX 25: SPECIFIC BIOGAS PRODUCTION RATE IN REACTOR 1+2

m³/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	1.328	0.402	1.160	1.367	1.533	1.622	1.920
HLD 2							
HLD 3a	0.945	0.336	0.808	0.947	1.068	1.132	1.697
HLD 1b	1.092	0.106	0.943	1.118	1.247	1.327	1.790
HLD 3b	0.847	0.235	0.734	0.847	0.959	1.015	1.332
HLD 1a	1.227	0.002	1.062	1.227	1.390	1.487	2.098
HLD 4	0.909	0.675	0.827	0.892	0.993	1.044	1.113
CD 25 °C b							
CD 25 °C a							
CD 1	0.486	0.124	0.433	0.487	0.542	0.569	0.715
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

TABLE ANNEX 26: SPECIFIC TOTAL SOLIDS REMOVAL RATE IN REACTOR 1

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	3.10	0.00	2.39	3.22	4.03	4.37	6.54
HLD 2							
HLD 3a	3.57	0.04	2.50	3.26	4.09	4.62	12.88
HLD 1b	3.15	0.17	2.16	2.76	3.72	5.12	9.06
HLD 3b	2.51	0.96	1.56	2.64	3.15	3.78	5.07
HLD 1a	2.73	0.00	2.18	2.77	3.32	3.68	6.96
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2	1.38	0.74	1.16	1.40	1.65	1.68	1.92
CD 3	0.59	0.00	0.31	0.60	0.85	0.98	2.06
CD 4	0.55	0.00	0.39	0.47	0.71	0.75	1.45
CD 5	0.74	0.61	0.66	0.68	0.76	0.84	0.97
CD 6							
CD 7c	0.21	0.08	0.15	0.19	0.25	0.26	0.47
CD 7a	0.26	0.18	0.23	0.24	0.28	0.30	0.39
CD 7b	0.22	0.14	0.18	0.20	0.27	0.27	0.30

Annex

TABLE ANNEX 27: SPECIFIC TOTAL SOLIDS REMOVAL RATE IN REACTOR 2

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	2.17	0.00	1.81	2.23	2.57	2.81	4.16
HLD 2							
HLD 3a	0.63	0.07	0.37	0.52	0.86	1.01	2.21
HLD 1b	0.50	0.00	0.29	0.48	0.71	0.77	1.86
HLD 3b	0.60	0.15	0.32	0.49	0.75	0.89	2.84
HLD 1a	0.58	0.00	0.31	0.56	0.80	0.93	2.45
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

TABLE ANNEX 28: SPECIFIC TOTAL VOLATILE SOLIDS REMOVAL RATE IN REACTOR 1

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	3.090	0.000	2.337	3.226	3.867	4.178	5.846
HLD 2							
HLD 3a							
HLD 1b	2.807	0.644	2.105	2.677	3.331	3.877	6.524
HLD 3b							
HLD 1a	2.642	0.075	2.197	2.688	3.134	3.326	5.079
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2	1.260	0.851	1.095	1.310	1.422	1.460	1.558
CD 3	0.597	0.000	0.427	0.612	0.765	0.837	1.231
CD 4	0.595	0.000	0.477	0.540	0.729	0.779	1.433
CD 5	0.474	0.443	0.457	0.470	0.490	0.498	0.510
CD 6							
CD 7c	0.324	0.196	0.275	0.311	0.351	0.376	0.493
CD 7a	0.347	0.279	0.325	0.330	0.348	0.369	0.473
CD 7b	0.314	0.222	0.277	0.334	0.342	0.360	0.391

Annex

TABLE ANNEX 29: SPECIFIC TOTAL VOLATILE SOLIDS REMOVAL RATE IN REACTOR 2

kg/(m³*d)	Average	Min	25%	50%	75%	85%	Max
HLD 1c	1.386	0.084	1.165	1.418	1.664	1.785	2.340
HLD 2							
HLD 3a	0.444	0.000	0.285	0.435	0.593	0.696	1.376
HLD 1b	0.422	0.000	0.274	0.419	0.551	0.650	1.135
HLD 3b							
HLD 1a	0.468	0.000	0.299	0.440	0.617	0.704	2.185
HLD 4							
CD 25 °C b							
CD 25 °C a							
CD 1							
CD 2							
CD 3							
CD 4							
CD 5							
CD 6							
CD 7c							
CD 7a							
CD 7b							

Annex

ZOOM FIGURES CH. 7

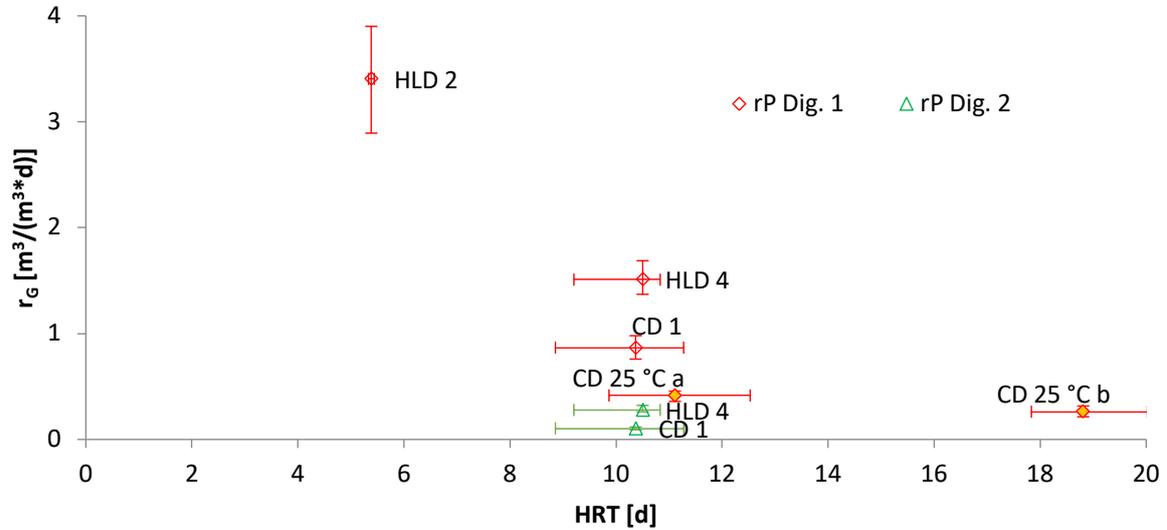


FIGURE ANNEX 6: Biogas production rate in the first and second digester

Annex

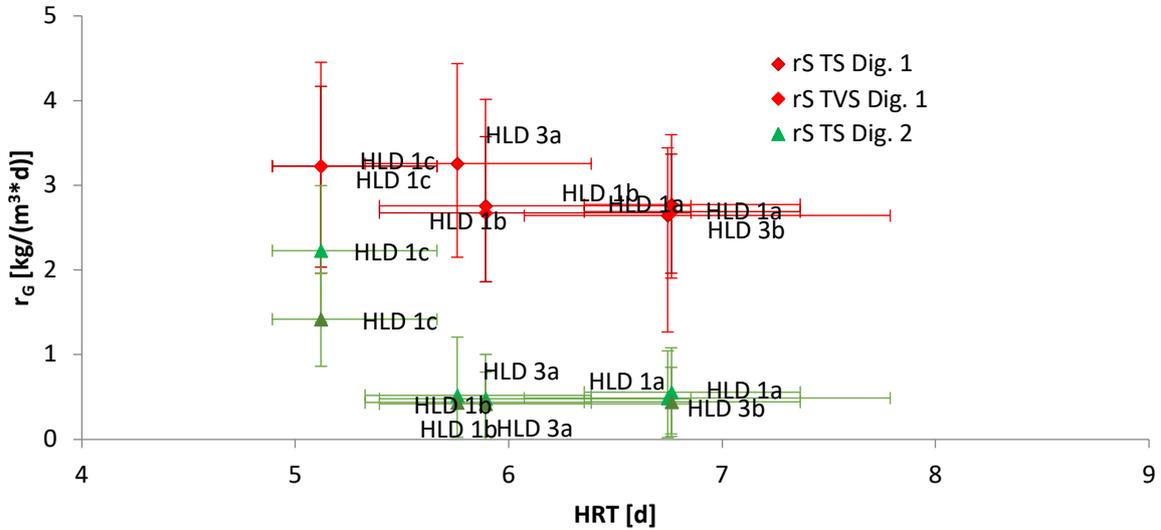


FIGURE ANNEX 7: Substrate removal rates in the first digester considering TS and TVS measurements