



Thermal efficiency and biogas production of a small-scale anaerobic digester

Student: Alejandro Deville del Aguila

Supervisor: Dr Ilan Adler

MSc Engineering for International Development

Department of Civil, Environmental & Geomatic Engineering

University College London

Abstract

This project sought to gain a deeper understanding of the relationship between temperature and gas production of a low-cost, small-scale anaerobic digester under psychrophilic and mesophilic conditions. A thermal analysis of the system was conducted. It was found that the digester was placed in unfavourable conditions for thermal gain as plants surrounding the system reduced its ambient temperature by 6 °C as compared to the rest of the greenhouse. Moreover, it was found that the slurry inside the digester experiences a daily temperature variation of 3°C, fluctuating between the psychrophilic and mesophilic regimes on a daily basis, resulting in a reduction of the biogas yield. The thermal model developed has an accuracy of 1.66 °C (8.2%) for the average digestate temperature.

It was observed that the digester was oversized as the manure produced could not meet the design loading rates. Results showed that the digester yielded an average of 397 litres of biogas per day. However, it was nearly 2m³ less than the value obtained by biogas production model. This difference is attributed to the irregular loading patterns, excessive retention time, accumulation of suspended solids and daily temperature variations experienced by the system.

Acknowledgements

I would like to thank Dr Ilan Adler for his guidance, and support provided throughout the entire project.

In addition, I would like to thank James Taylor from Surrey Docks Farm, who not only loaded the digester but helped with the installation of the equipment and took readings necessary for the development of the research. Furthermore, I thank the volunteers and staff at Surrey Docks Farm for the collection of the manure and for providing a friendly work environment.

I would also like to thank Dr Judith Zhou for providing the equipment necessary for the development of the project.

Finally, I would like to thank my friends and family who supported and encouraged me during the entire program.

Abbreviations and Nomenclature

AD	=	Anaerobic Digestion	
H ₂ S	=	Hydrogen Sulphide	
LCFA	=	Long Chain Fatty Acids	
VFA	=	Volatile Fatty Acids	
CO ₂	=	Carbon Dioxide	
NH ₃	=	Ammonia	
CH ₄	=	Methane	
H ₂	=	Hydrogen	
CH ₃ COOH	=	Acetic Acid	
OLR	=	Organic Loading Rate	
HRT	=	Hydraulic Retention Time	
TS	=	Total Solids	
VS	=	Volatile solids	
C:N	=	Carbon to Nitrogen ratio	
H ₂ O	=	Water	
CSTR	=	Completely Stirred Tank Reactor	
ADM1	=	Anaerobic Digestion Model 1	
PTD	=	Plastic Tubular Digester	
T	=	Temperature	
σ	=	Stefan-Boltzmann constant	W/m ² *K ⁴
λ	=	Thermal conductivity	W/m*K
ν	=	Kinematic viscosity	m ² /s
ε	=	Thermal emissivity	
ρ	=	Density	kg/m ³
β	=	Volumetric thermal expansion coefficient	1/K
Pr	=	Prandtl number	
Ra	=	Rayleigh Number	
Nu	=	Nusselt Number	
hc	=	Convective Heat transfer coefficient	W/m ² *K
g	=	Gravity	m/s ²
e	=	Width	m
Lc	=	Characteristic length	m
A	=	Area	m ²
C _w	=	Water heat capacity	kJ/kg*K
θ	=	HRT	Days
B ₀	=	Biochemical methane potential	L CH ₄ /kg*VS
S ₀	=	Volatile solids concentration	g/kg
K	=	Relative substrate-microorganism kinetics	
Y _v	=	Methane production rate	L CH ₄ /day*m ³
μ _m	=	Microorganisms maximum production rate	Day ⁻¹
Subscripts:			
bg	=	Biogas	
dg	=	Digestate	
co	=	Digester surface	
gh	=	Greenhouse Ambient	
i	=	insulation	
Min	=	Manure influent	
Mout	=	Manure effluent	

Table of Contents

Abstract	2
Acknowledgements.....	3
Abbreviations and Nomenclature	4
List of figures	7
List of tables	8
1. Introduction:.....	9
1.1. Problem description.....	9
1.2. Aims and Objectives.....	9
1.3. Background	9
1.4. Report structure:.....	10
2. Literature Review:.....	11
2.1. Anaerobic digestion process.....	11
2.2. Parameters affecting AD.....	12
2.2.1. Temperature.....	12
2.2.2. Feedstock characteristics	14
2.2.2.1. Carbon and Nitrogen.....	15
2.2.2.2. pH.....	15
2.2.3. Retention Time	15
2.3. Increasing thermal efficiency	16
2.3.1. Ground temperature	16
2.3.2. Solar heating	16
2.3.3. Active heating.....	17
2.3.4. Heap composting and hot charging	17
2.4. Anaerobic digestion in cold weathers.....	17
2.5. Thermal modelling of Anaerobic Digestion: past studies.....	19
2.6. Biogas production modelling.....	21
2.7. Surrey Docks Farm and previous studies	22
2.7.1. Previous studies at Surrey Docks Farm.....	23
3. Materials and Methodology.....	25
3.1.1. Installation process.....	26
3.1.2. Thermal model validation.....	27
3.2. Biogas production.....	27
4. Thermal and biogas production modelling	29
4.1. Thermal model.....	29

4.1.1.	Modelling of the convective heat transfer from the greenhouse air (T_{gh}) to the digester cover (co), $Q_{c\ gh - co}$	30
4.1.2.	Modelling the radiative heat transfer between the digestate (dg) and the digester cover (co), $Q_{r\ co - dg}$	31
4.1.3.	Modelling the convective heat transfer between the digestate (dg) and the cover (co), $Q_{c\ dg - co}$	31
4.1.4.	Modelling the heat transfer from the slurry (sl) to the digester's walls (w), $Q_{dg - w}$	32
4.1.5.	Modelling the heat transfer due to the manure flow, Q_{Min} and Q_{Mout} ...	32
4.1.6.	Solving process	33
4.2.	Biogas production model	34
5.	Results and discussion	36
5.1.	Thermal analysis	36
5.2.	Biogas production.....	41
6.	Sources of Error	43
7.	Concluding remarks.....	44
7.1.	Conclusions.....	44
7.2.	Recommendations for future work	44
	References	46
	Appendix 1. Digester Loading register	53
	Appendix 2. Temperature readings and model results. Expressed in °C.....	54
	Appendix 3. Biogas production model results	55
	Appendix 4. Risk Assessment.....	56

List of figures

Figure 1. Anaerobic Digestion process	12
Figure 2. Relative growth rate of psychrophilic, mesophilic and thermophilic methanogens.....	13
Figure 3. 2018 temperatures in the South East of England	14
Figure 4. Adobe greenhouse	18
Figure 5. Fix-cover digester with solar collectors.....	20
Figure 6. Elevation of the digester.. ..	25
Figure 7. Detailed cross-section of the greenhouse and digester.....	26
Figure 8. Extech TM20 Thermometer measuring T_{dg} installed.....	27
Figure 9. BK-G4 M gas meter.	28
Figure 10. Heat transfer phenomena occurring in the biodigester.	29
Figure 11. Temperatures registered.....	36
Figure 12. Southwark Council hourly temperatures.....	37
Figure 13. Correlation between T_{gh} and T_{dg}	38
Figure 14. Real T_{dg} vs. Modelled T_{dg}	39
Figure 15. Biogas daily production vs. average greenhouse temperature	42

List of tables

Table 1. Summary of previous AD-related projects at Surrey Docks Farm.....24

Table 2. Physical parameters used for the thermal model.....33

Table 3. Influent and effluent temperatures.....40

1. Introduction:

1.1. Problem description

Anaerobic digestion (AD) has gained international attention in the last decades due to its ability to treat organic waste and because of the benefits of its outputs: biogas and digestate. Biogas, composed mainly of methane and carbon dioxide can be used as an alternative source of energy for several activities such as cooking, and heating and is considered to be carbon-neutral. Additionally, the digestate produced (decomposed organic material) can become an additional source of income for farmers as it can be sold as soil fertiliser if treated appropriately.

However, both biogas and digestate, are affected by several factors, being temperature one of the most critical as it will influence the interrelationship of microbial groups and the speed that the organic material will decompose inside of the reactor (Chae *et al.*, 2008). At temperatures below 20°C, the growth rate of microorganisms responsible for the fermentation of the digestate falls sharply (Rebac *et al.*, 1995). As a result, the organic matter has to remain inside the digester for more extended periods of time as compared with higher temperatures, and the biogas production rate is heavily reduced. As a consequence, small to medium-scale (up to 100 m³) anaerobic digesters have been widely adopted in countries with tropical weathers and less considered in the northern hemisphere where temperatures are colder, and the biogas production is heavily constrained, and it may not be considered to be cost-effective.

1.2. Aims and Objectives

The study aims to find correlations between feedstock, thermal efficiency and biogas production under psychrophilic and mesophilic conditions. Furthermore, the study also intends to provide useful recommendations to increase the thermal efficiency of the system and information on good practices for biogas thermal analysis for future small-scale AD research and development. Moreover, the project intends to provide an accurate thermal and biogas production models representative of the digester studied.

1.3. Background

The project is based in Surrey Docks Farm, London, where there are two plug-flow polyethylene tubular anaerobic digesters working in tandem. Both reactors have already being studied by UCL undergraduate and graduate students, analysing the correlations of different parameters of the digesters.

1.4. Report structure:

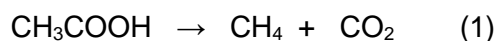
Chapter 2 presents the literature review, which includes an overview of the anaerobic digestion process and their key parameters, biogas production and its relationship with thermal efficiency, past investigations regarding thermal efficiency and modelling of anaerobic digesters in cold climates, and previous studies in Surrey Docks Farm. Chapter 3 discuss the experimental methodology and materials used in the project. Chapter 4 presents a detailed description of the thermal analysis and biogas production model. Chapter 5 shows the results of the project and their discussion. Chapter 6 presents the sources of error. Finally, Chapter 7 the concluding remarks.

2. Literature Review:

2.1. Anaerobic digestion process

Anaerobic digestion (AD) is a natural process where organic matter is broken down due to microbial activity in an environment free of oxygen. AD systems use organic waste from different sources such as animal manure, wastewater and by-products of the food-processing industry as feedstock (Wellinger, Murphy & Baxter, 2013). AD converts the feedstock into two main outputs: biogas and digestate (biol). Biogas is composed mainly of methane (55-65%) and carbon dioxide (40-45%), along with other impurities such as water and hydrogen sulphide (H₂S) (Wellinger, Murphy & Baxter, 2013). Moreover, biogas it's considered to be a renewable energy source as it can be used as a fuel to produce electricity, heating and even as a vehicle fuel if enhanced and treated (Börjesson & Mattiasson, 2008). In addition, as a result of the decomposition of the organic matter, a nutrient-rich digestate is produced, which can be used as a soil fertiliser.

It is considered that the AD process has four main phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis. During hydrolysis, complex organic matter in the feedstock, mainly carbohydrates, proteins and fats, are broken down into sugars, amino acids and long chain fatty acids (LCFAs), respectively (Steinhauser & Deublein, 2011). The second stage, acidogenesis, further decompose the material into volatile fatty acids (VFAs), ammonia (NH₃), carbon dioxide (CO₂), hydrogen sulphide (H₂S) and other compounds (Appels et al., 2008). Acidogenesis includes fermentation and anaerobic oxidation (β-oxidation), which are carried out by fermentative acidogenic and acetogenic bacteria, respectively (Chen et al., 2014). Furthermore, in the third phase of the process, acetogenesis, VFAs and LFCAs are fermented into acetic acid (CH₃COOH), CO₂, methane (CH₄) and hydrogen (H₂) (Xu, Li & Wang, 2015). Finally, in the methanogenesis phase, acetic acid, CO₂ and H₂ produced in previous phases are used by methanogenic bacteria to produce CH₄ and CO₂, as shown in Equations 1 and 2. This final stage is critical to the production of biogas, as nearly 70% of the methane it's produced in this phase. Figure 1. illustrates the process and its different stages and the relationship between each element and stage



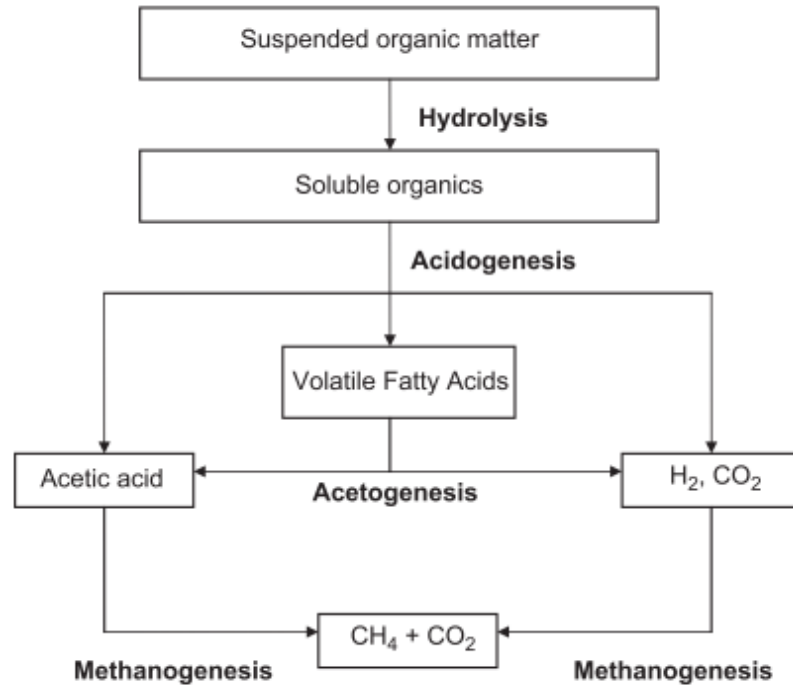


Figure 1. Anaerobic Digestion process (Appels *et al.*, 2008)

2.2. Parameters affecting AD

AD is a complex process where several factors affect its performance and the quality of their outputs. The interrelationship of working parameters such as type of digester with the feedstock characteristic is of critical importance for a proper performance of the system (Ferrer *et al.*, 2011). Furthermore, as explained in section 2.2.1., the working temperature is vital as it is one of the limiting parameters of the design and its use to predict the behaviour of the slurry inside the reactor.

2.2.1. Temperature

The working temperature of AD of critical importance for the proper performance of the system. It is recognised that there are three bacterial groups responsible for AD operating under three different temperature ranges: thermophilic bacteria at 45-60°C mesophilic around 20-40°C and psychrophilic at temperatures lower than 20°C (Buysman, 2009). Moreover, higher temperatures increase the decomposition rate of organic matter, thus reducing the retention time and increasing its cost-effectiveness. However, methanogens are very susceptible to temperature changes, being thermophilic bacteria only able to

withstand temperature changes of $\pm 1^{\circ}\text{C}$ while mesophilic bacteria can tolerate temperature fluctuations of $\pm 2.8^{\circ}\text{C}$ (Surendra *et al.*, 2013).

The growth rate of microbial activity diminishes with temperature, and under psychrophilic conditions, it is below its optimum, as illustrated in Figure 2. As a result, chemical and biological reactions occur at a much slower pace than in mesophilic and thermophilic conditions (Lettinga, Rebac & Zeeman, 2001). It is considered that methane production is doubled each 10°C increase in the temperature of the digester in the mesophilic range. Moreover, Wellinger (1999) found that the speed of degradation is half at 22°C as compared to those working at 35°C .

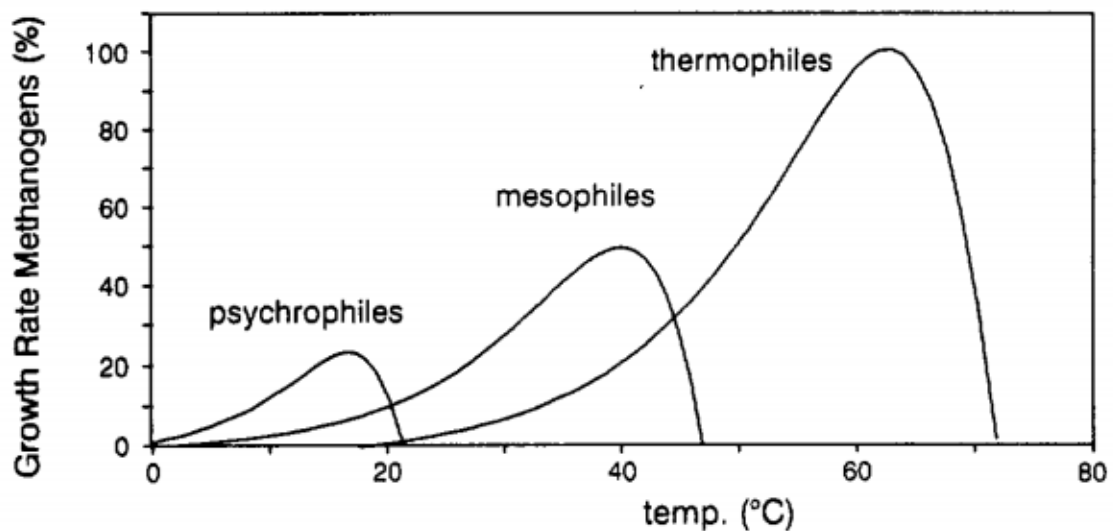


Figure 2. Relative growth rate of psychrophilic, mesophilic and thermophilic methanogens (Van Lier, Rebac & Lettinga, 1997).

Bouallagui *et al.*, (2004) studied and compared the performance of a tubular digester treating fruit and vegetable waste under psychrophilic, mesophilic and thermophilic environments. An 18-litre digester was fed with different total solids (TS) concentrations of 4, 6, 8 and 10% with varying retention times of 10, 15 and 20 days for each temperature range. For the start-up, the digester was inoculated with a sludge of a mesophilic vegetable and fruit digester.

The biogas produced was measured on a daily basis. It was found that the biogas conversion was improved with temperature increase from psychrophilic to thermophilic conditions. Furthermore, biogas production in the thermophilic range was 144% and 41% higher than under psychrophilic and mesophilic conditions, respectively. Biogas

composition was also measured and remained constant regardless of the working temperature, ranging between 58%-62% of methane. Moreover, inhibition under the psychrophilic and mesophilic range was identified with a TS concentration of 8% and 10%, respectively. This inhibition is attributed to an accumulation of suspended solids, associated with a reduced microbial activity due to temperature, variations and an irreversible decrease of the pH (Bouallagui *et al.*, 2004).

As seen in Figure 3., the South East of England, where London is located, experiences temperatures that fall in the psychrophilic range the majority of the year, making the operation small-scale AD complex and not cost-effective due to the high retention time and low biogas production. The financial analysis made by Toyozawa *et al.*, (2017) of the second Surrey Docks Farm anaerobic digester obtained a payback time of 6 years, estimating a merely £90 annual save for the use of biogas and, assuming the commerce of the entire production of digestate as fertilizer (which does not occur in practice) accounting over 75% of the digester's profits. It can be seen the need to study and increase the thermal efficiency of small-scale, low-cost AD and maintain an appropriate working temperature.

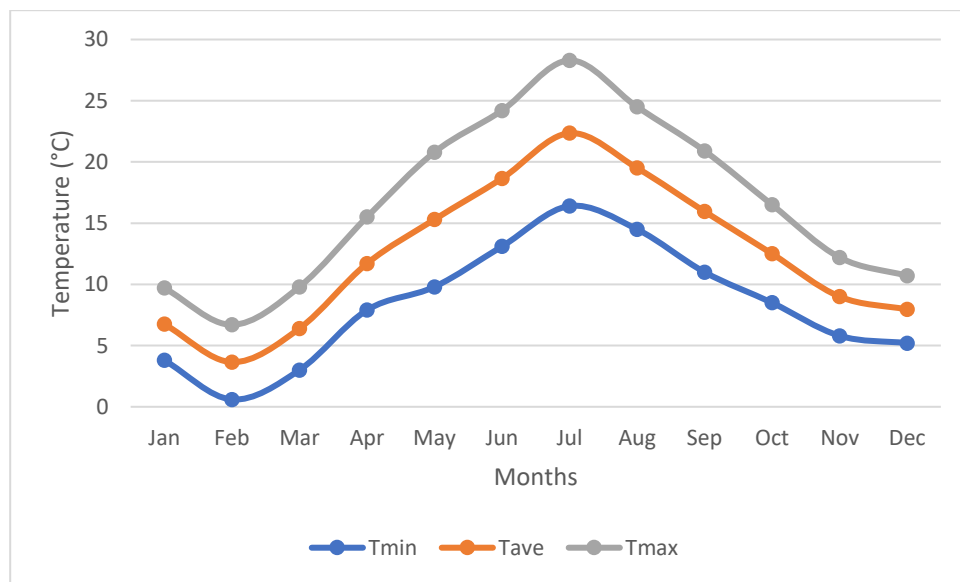


Figure 3. 2018 temperatures in the South East of England (Heathrow station) (Metoffice.gov.uk, 2019)

2.2.2. Feedstock characteristics

Several studies such as Ozturk (2012), Dioha *et al.*, (2013) and Khalid *et al.*, (2011) have analysed different types of feedstock and their performance during AD. They examined

parameters such as TS, Volatile Solids (VS), carbon to nitrogen ratio (C: N) and pH to identify the different relationships in each phase of the process and how it is translated into biogas production and composition.

2.2.2.1. Carbon and Nitrogen

The carbon content in the feedstock is one of the most important characteristics as it will not only determine the CH₄ content (more carbon atoms, more methane percentage in biogas) (Steinhauser & Deublein, 2011) but it will influence most of the microbial activity inside of the digester. Moreover, C: N is of critical importance, and it should be maintained between 20-35 to achieve an adequate decomposition process (Khalid *et al.*, 2011; Ozturk, 2012). The high value of carbon atoms will increase the formation of CO₂ and lower the pH value. A high concentration of nitrogen will enhance the production of ammonia, increase the pH and reduce the number of microorganisms responsible for fermentation (Dioha *et al.*, 2013). If C: N is too high, the process is limited by the amount of nitrogen available and the resulting acidification delays the methanogenesis process. If C: N is too low, the concentration of ammonia will increase to reach the point of being toxic for the bacterial population and may inhibit the system (Ozturk, 2012; Chen *et al.*, 2014).

2.2.2.2. pH

Microorganisms responsible for the methanogenesis of the organic material in AD are highly sensitive to pH changes in the slurry. If a pH of 6 or below is obtained, the system will start to accumulate VFAs, killing methanogens, resulting in a continual increase in VFAs, reduction of pH and biogas output (Mann, 2014).

Several studies have concentrated their efforts in obtaining the optimum range of pH for optimum performance of methanogenic bacteria. Turkdogan-Aydinol & Yetilmezsoy (2010), found that the optimum pH should be between 6.5 and 7.8 for microorganisms to thrive and reproduce for the mesophilic treatment of molasses wastewater. Moreover, Liu *et al.*, (2008) obtained optimal pH of 7.1 and 7.21 for mesophilic and thermophilic conditions respectively, resulting in a 35% increase of cumulative methane production when treating municipal solid waste.

2.2.3. Retention Time

The amount of time the feedstock stays inside of the reactor is of vital importance to both the composition and production of biogas and digestate. Both the organic loading rate

(OLR) and hydraulic retention time (HRT) have time as a variable. OLR describes the amount of volatile dry matter (VDM) entering the digester, while the HRT describes the period of time that the substrates stay in the digester. HRT and OLR are closely related, and are calculated as described in Equations 3 and 4, respectively:

$$HRT \text{ (days)} = \frac{\text{Digester Volume (L)}}{\text{Total Loading Rate} \left(\frac{\text{L}}{\text{day}}\right)} \quad (3)$$

$$OLR \text{ (kgVDM/m}^3\text{day)} = \frac{\text{Substrat input (kg/day)*DM(\%)*VDM (\% of DM)}}{\text{digester net volume (m}^3\text{)}} \quad (4)$$

Both must be chosen considering the feedstock characteristics and availability, digester size and working temperature. If they are not chosen appropriately or followed, VFAs concentrations may increase due to the washout of methanogenic bacteria causing an incomplete break down of organic compounds (Appels *et al.*, 2008; Wellinger, Murphy & Baxter, 2013).

2.3. Increasing thermal efficiency

Due to the constraints presented by low-temperature AD and the effects on low biogas yields, several methods have been tried to improve the working temperature in adverse conditions. The following subsections present different ways to increase the working temperature of anaerobic digesters.

2.3.1. Ground temperature

Most reactors facing extreme conditions are built entirely or partially (as the digesters in Surrey Docks Farm) buried, to gain heat using soil temperature which is maintained nearly constant throughout the year (Florides & Kalogirou, 2007). Being underground also implies that the equipment is not exposed to low ambient temperature, high winds and precipitation.

2.3.2. Solar heating

Solar heating can be used in AD both directly or indirectly. Direct assistance means that the digester or surface around or over it is heated with solar energy. In contrast, indirect solar heating supposes that the captured solar energy is transported by a medium to the required location (Buysman, 2009). However, the use of solar heating in the anaerobic digestion process may affect the process stability during thermophilic AD and may increase the probability of inhibition due to higher free ammonia concentration at increased temperatures (El-Mashad, Van Loon & Zeeman, 2003),

An example of direct heating is achieved by glazing or blackening of the digester and surrounding soil. Kishor *et al.*, (1988) studied the effect of blackening and glazing the ground on top of an 8 m³ fixed drum digester in India. The research found that for tropical weathers, single glazing and blackening was sufficient to maintain the slurry inside of the digester at temperatures between 28-35°C. However, for cold climates, the combination of surface blackening and double glazing is not enough, and approximately 50% of the biogas produced have to be burned in order to reach the desired slurry temperatures, assuming a 60% efficiency of the heating system (Kishor *et al.*, 1988). The use of a greenhouse is also a mean of direct solar heating as it captures and retains solar energy in the surrounding areas (Buysman, 2009). In contrast, an indirect solar heating system needs more components to assemble the system. Most consist of solar panels (or solar collectors), piping system between the panels and digester, and a storage tank (Kocar & Eryasar, 2007).

2.3.3. Active heating

Active heating supposes the use of an electric current or a vehicle exhaust to heat the digester. However, the system is not suitable for small-scale digesters at a household level because the use of such fuels leads to excessive heating costs, making its usage uneconomical, and defeating its purpose (Buysman, 2009).

2.3.4. Heap composting and hot charging

Aerobic composting of organic waste releases a substantial amount of heat, reaching temperatures up to 80°C (Misra, Roy & Hiraoka, 2003) can be harnessed and used as a mean to heat the digester. In contrast, hot charging supposes the heating of water prior to mixing it with manure. Moreover, if the digester temperature is significantly lower than the inlet slurry, the already acclimatised microorganisms inside the digester will be affected negatively (Buysman, 2009).

2.4. Anaerobic digestion in cold weathers

The study of small-scale anaerobic digesters in the presence of psychrophilic conditions have been carried out to improve the thermal efficiency of the system and enhance biogas production.

Poggio *et al.*, (2009) installed thirteen 6 m³ capacity low-cost plastic tubular digesters (PTD) in the Peruvian Andes and monitored them over two years. Their goal was to analyse the performance of the system under cold Andean conditions where the average

annual ambient temperature rarely exceeds 10°C (Poggio *et al.*, 2009a). Due to the unfavourable conditions, the digesters are semi-buried and placed inside of a massive adobe wall greenhouse with a polyethene roof, as seen in Figure 4. Moreover, the area has high solar insolation throughout the year ranging 6-6.5 kWh/m²/day, which as discussed in Section 2.3.2., can improve the working conditions in cold weathers significantly. The digesters were insulated placing a layer of straw between the ground and the reactor. In addition, a plastic sheet was placed between the straw layer and the soil to prevent decomposition of the insulation and stop plants from growing inside of the digester as the evapotranspiration of plants can affect the inner temperature of the greenhouse, reducing the thermal efficiency of the system.



Figure 4. Adobe greenhouse (Poggio *et al.*, 2009a)

As a result, they observed that the greenhouse not only helped gain heat during great solar irradiation times during the day but also reduced heat loss in the night time and reduced the photo-degradation of the digester due to reduced ultraviolet radiation received. Moreover, the digesters gained sufficient heat so that the inner temperature was 10°C higher compared to the surrounding ambient. However, the daily temperature fluctuation, which can be of up to 14°C between day and night, harmed the performance of the digester. The daily biogas production obtained was enough for 3.5 hours' worth of cooking and did not meet the needs of the users who had to recur to traditional cooking fuels (Poggio *et al.*, 2009a).

Similarly, Ferrer *et al.*, (2011) installed four plastic and PVC tubular digesters in different locations of the Peruvian altiplano, at various altitudes between 2800 to 3900 m.a.s.l. The digesters were fed with a mixture of cow manure and water with different manure to water ratios (1:4 and 1:2), and with HRTs varying from 60 to 100 days. Furthermore, the digesters were kept inside of a greenhouse and partially buried to reduce the heat loss. All the reactors worked in the psychrophilic range. The digesters had an average specific biogas production of $0.36 \text{ m}^3\text{kg}^{-1} \text{ VS}^{-1}$ with a CH_4 content of 60-63%.

2.5. Thermal modelling of Anaerobic Digestion: past studies

Due to the importance of temperature in the anaerobic digestion process, as discussed in Section 2.2.1., several studies have analysed the thermal efficiency of different biodigesters. Moreover, because heat transfer phenomena in AD is closely related with several factors such as ambient temperature, wind speed and temperature of the feed, thermal modelling is a crucial element when designing any biodigester (Hreiz *et al.*, 2017b). Thermal simulation can provide essential insights on the system heat requirements, help determine which phenomena contributes most to heat losses of the digester and possible solutions to tackle them, improving the working conditions. Also, a thermal model can be used jointly with biochemical models increasing the accuracy of biogas production prediction (Hreiz *et al.*, 2017b).

Kishore (1989) developed a steady-state heat transfer analysis for a family sized ($2\text{m}^3/\text{day}$) fixed-dome biogas plant considering heat losses from the ground surface to the digestate inside the reactor. The study found that the temperature inside the digester can be raised up to $7 \text{ }^\circ\text{C}$ if the input slurry temperature was raised to at least $50 \text{ }^\circ\text{C}$ (hot charging). Moreover, the digester presented an increase of $5 \text{ }^\circ\text{C}$ of when being placed inside of a greenhouse. However, thermal efficiency solutions such as hot charging, insulation and greenhouse applied alone would not result in a significant thermal efficiency increase. Furthermore, the study concluded that burning the biogas to provide external energy for heating will not result in net energy gain. Singh, Singh & Bansal, (1985) proposed a combination of double glazing and the installation of a shallow solar pond water heater on top of a fixed dome digester to increase the influent slurry temperature and reduce heat losses through the gas holder.

Perrigault *et al.*, (2012) analysed the thermal efficiency of a cold climate, small-scale plug-flow tubular digester in the Andean plateau used by a family for cooking and heating purposes. The equipment is placed inside of an adobe greenhouse similar to the system

analysed by Poggio *et al.*, (2009a). A simple time-dependent model was developed using solar irradiation, ambient temperatures, wind speed and the greenhouse as inputs. Authors found that the working temperature of the digesters increased by 8.4°C in comparison to the surrounding ambient temperature. Garfí *et al.*, 2011 after analysing a similar system, with conditions alike, documented that the temperature inside the digester maintained an almost regular temperature of 20 °C while the temperature inside the greenhouse experienced a daily temperature fluctuation between 60 °C and 15 °C, and ambient temperature varied from 10 °C to 30 °C in the same period.

K. G. Gebremedhin *et al.* (2005) studied the heat transfer phenomena occurring in a buried, semi-buried and completely above ground plug-flow digesters when the surrounding soil is frozen. A 0D model predicting heat requirements was produced to predict the energy requirements. It was identified that for a 60m³/day capacity, an increase of only 1 °C of the feed would result in a considerable reduction of energy requirements, saving up to 224300 kJ/day.

Axaopoulos *et al.* (2001) developed a mathematical model for simulating the thermal performance of a solar-heated digester. The study analysed the performance of a semi-buried 45 m³ fix cover digester treating swine manure in Greece. The roof of the system is made of flat-plate solar collectors using water as heating fluid. The panels were painted black and insulated with 50 mm glass wool. The heated water is then pumped through a bank of heating coils inside of the digester when needed. Figure 5. presents the model of the digester and heating process. The system is activated when the temperature difference of the collector and the slurry in the digester is 7°C and when the temperature inside the digester is less than 35°C (Axaopoulos *et al.*, 2001).

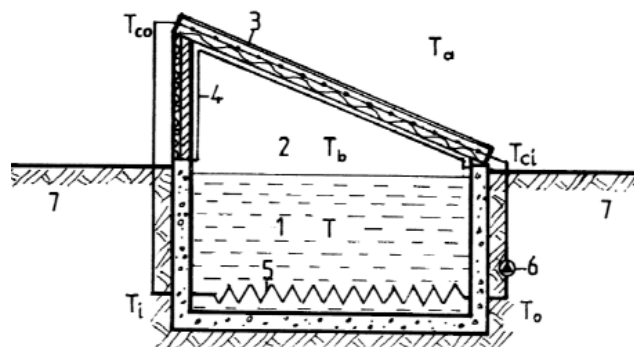


Figure 5. Fix-cover digester with solar collectors. 1, slurry; 2, produced biogas; 3, solar collector; 4, plastic cover; 5, heating coils; 6, pump; 7, soil (Axaopoulos *et al.*, 2001).

The digester is fed daily with 12 m³ of swine manure and water mix with an average VS content of 6.8% and a concentration between 5.3 – 19.8 kg_{VS} m⁻³. Moreover, the methane content of the produced biogas was measured on a daily basis, with a mean value of 73.8%. It was observed that the slurry temperature was higher than the produced biogas. This is mainly attributed to the operation of the heating systems and, to the effects of the surrounding soil discussed in Section 2.3.1. The solar irradiance reached an average peak of nearly 800 W/m² each day causing that the temperature of the water flowing through the solar collectors was much higher than the surrounding temperature. The ambient temperature measured ranged between 18 – 32°C while the solar collector ranged 27 - 44°C. The use of a solar heating system was thus responsible for increasing the digester temperature and reaching nearly optimum working conditions and for maintaining it stable helping the stability of microbial activity inside the digester as discussed in Section 2.2.1.

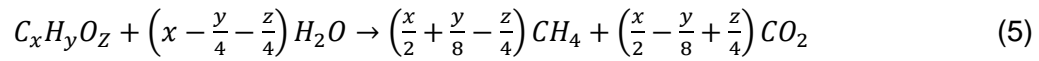
Hreiz *et al.* (2017) studied the heat transfer phenomena of partially buried anaerobic digesters. The authors developed a model to calculate the temperature fluctuations of the digestate and biogas inside the digester as a function of climatic conditions. The simulation also includes the effects of rain events in energy transfer. In addition, the heat losses to the surrounding soil have been calculated considering the long-term impact of the digester's temperature on the soil. This pseudo-steady simulation approach differs from most of the related literature, which considers the surrounding soil as an undisturbed body and overestimates heat losses.

2.6. Biogas production modelling

Biogas production models are a useful tool for the designing and prediction of the digester performance. Also, production models can provide a better understanding of the process dynamics occurring in each phase of the treatment, help identify possible during the operation and optimisation opportunities (Turkdogan-Aydinol & Yetilmezsoy, 2010). AD modelling has improved in complexity towards more complicated biochemical relationships over the last decades. Early-stage models used a single-stage kinetics to calculate the degradability and gas production at steady state. In contrast, recent simulation has implemented more complex biodegradation of organic materials under sophisticated processes (Nguyen, H. H., 2014).

Moreover, with knowledge of the feedstock chemical composition, the maximum methane yield that can be obtained through degradation can be calculated using the

stoichiometric formula developed by Buswell & Mueller (1952) (Achinas & Euverink, 2016):



Currently, the Anaerobic Digestion Model 1 (ADM1) is the most comprehensive model for modelling AD processes and nowadays is the most widely used by for bot practical and academic applications. It describes the main biochemical and physio-chemical reactions occurring in AD (Poggio *et al.*, 2016). ADM1 was developed by the IWA Anaerobic Digestion Task Group as a joint effort of several experts with the purpose to create a generalised model for AD. The model is divided in three main analysis: biochemical, physio-chemical and mass transfer reactions (Batstone *et al.*, 2002; Nguyen, H. H.,2014). Although it is accepted that AD comprises four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis as discussed in Section 2.1.) ADM1 also includes a disintegration step beforehand because it is thought to precede them and provide the substrates for hydrolysis to take place (Nguyen, H. H.,2014). ADM1 success is because the mechanisms are well expressed; the results are more compatible and comparable and provide a baseline for further developments. Furthermore, it can be used in a wide range of applications and can be coupled with additional wastewater treatments and help model all the system. However, the model assumes first order kinetics in the hydrolysis step, which it may not be accurate because it is suggested that types of material, feedstock and biomass concentration should also be considered (Batstone *et al.*, 2002; Nguyen, H. H.,2014).

2.7. Surrey Docks Farm and previous studies

FAO (2003) defines urban as the production and distribution of food within a metropolitan area. However, the definition varies with different authors, mainly to the extension of what is considered urban agriculture and whether including peri-urban farming as urban activities as well (Azunre *et al.*, 2019). Urban agriculture has gained attention over the last decades due to growing urban food security concerns and as a viable strategy for the urban poor to generate an extra income (Armar-Klemesu, 2000).

However, there have been increasing concerns regarding the risks that urban farming possesses to the general public. Air pollution and foul odours due to ammonium, methane, nitrogen oxide and others gases; as well as toxic contamination from chemical fertilisers and pesticides possess a big concern for neighbouring communities (Brown &

Jameton, 2000). Moreover, inadequate waste management can create a platform for spreading diseases. Waste gases from compost piles have been associated with dysentery, tuberculosis and cancer and mismanagement of nearby untreated wastewater systems can contaminate the crops, resulting in diseases such as cholera (Bryld, 2003). Solutions such as AD presents an efficient alternative for tackling space problems and health concerns due to waste mismanagement, as the process decompose the organic waste in an enclosed environment, reducing the chance of diseases to spread.

Surrey Docks Farm is a community-based urban farm located in the south-east of London. First established in 1975 near the entrance of Greenland Dock and the River Thames, its initial purpose was to grow crops and raise livestock to produce food from an unused land considered wasteland. In 1986 was relocated to its current 2.2-acre site on the River Thames at South Wharf. Nowadays the farm counts with an orchard and various animals, from cows, goats and pigs to guinea pigs and ferrets, ducks and geese. It works closely with the local community providing farming and food production educational programs year-round (Surrey Docks Farm London, 2019).

2.7.1. Previous studies at Surrey Docks Farm

The first anaerobic digester in Surrey Docks Farm was installed in 2014 by a team of third-year students from UCL (Bruce et al., 2014). After this installation, there have been several studies with the digesters as a subject. Table 1. presents a summary of the different research projects conducted in the anaerobic digesters at the farm.

Table 1. Summary of previous AD-related projects at Surrey Docks Farm.

Project	Summary	Year	Reference
Surrey Docks Farm anaerobic digestion: system design (1 st digester)	This project describes the process of the design and installation of a plug-flow tubular digester (first digester) at Surrey Docks Farm. A feasibility study was made reviewing the components needed for the system regarding the manure availability of the farm and working conditions. The study found the digester should have a length of 64 m with a 1.1 m width. However, due to constraints and resources limitations, an 8.5 m digester was installed. The recommended HRT varied with the time of the year, taking into account the temperature difference during the year resulting in 45 and 35 days in winter and summer respectively, with a manure to water ratio of 1:4.	2014	Bruce, et al., (2014)
Start-up and Performance Testing of an Innovative Biodigester Model on an Urban Farm	The purpose of this research was to start-up and monitor the performance of the anaerobic digester installed by Bruce et al. (2014). The study was conducted during the summer months and concluded that the reactor was predicted to perform appropriately. However, suggested slurry mix pre-heating before entering the digester during winter. The digestate produced was analysed and given a market value of £4.21/m ³ . However, further digestate analysis is proposed in order to get an idea of its true value. Also, a pasteurisation unit is recommended for the digestate can be sold.	2014	Mann, (2014)
Monitoring of a small-scale anaerobic digester in an urban farm in London	The aim of this research was to gain a better understanding of AD, and the biogas uses. The biogas produced and digestate were continuously analysed and correlate essential parameters such as gas composition, TOC and pH. Furthermore, an engine was run with biogas sample, and its performance was compared with the use of diesel as a fuel. The results show that biogas combustion supposed only reductions of NO _x emissions in comparison to diesel but has a lower thermal efficiency.	2015	Franzellin, & Paw, (2015)
Sterilisation of Effluent from an anaerobic digester using novel methods	This research analysed the efficiency of lime sterilisation of the digester effluent. Tests were done using culture-based methods and chemical analysis. It was found that lime sterilisation kills over 98% of bacteria present in the digestate. In addition, TOC and phosphate content were reduced, while the potassium concentration increased, thus not affecting the digestate market value. In addition, molecular methods are recommended for future studies to identify the bacteria surviving the lime sterilization and determine whether or not lime sterilisation is sufficient.	2016	Gray, (2016)
Design report of the installation of an anaerobic digester at Surrey Docks Farm (2 nd digester)	This report presents the design and installation of a second tubular plug-flow anaerobic digester at Surrey Docks Farm. The design proposed will be able to treat 0.09 m ³ /day and 0.07 m ³ /day of manure during summer and winter, respectively. Furthermore, the analysis shows that a second digester will reduce the farm organic waste by 41%. Due to the low temperatures during winter, electrical heating wires were installed predicting that the internal temperature of the digester can be raised 9 °C during winter. Biogas production was estimated to be of 470 m ³ /year and considering its energy content, a £90 reduction in the annual energy costs is predicted. In addition, the income generated by selling the digestate was estimated to be £390 per annum, giving the digester a payback time of 6 years.	2017	Toyozawa, et al., (2017)

3. Materials and Methodology

Surrey Docks Farm counts with two plug flow tubular biodigesters manufactured by Sistema Biobolsa, a Mexican organisation with presence in Latin America, Kenya and India (Sistema.bio, 2019). The first digester processes raw manure-slurry and the resulting digestate is then pumped to the second digester, inside of a different polytunnel greenhouse to further decompose the organic matter. The resulting biogas is then directed to a gas stove located in the middle of both used for domestic purposes. This research is centred in the first anaerobic digester

For the thermal analysis, six different locations were chosen to monitor the thermal behaviour of the system: manure slurry inlet (T_{Min}), slurry inside the digester (T_{dg}), between the digester bag and the ground insulation (T_i), at the biodigester surface (T_{co}), the digestate outlet (T_{Mout}) and the greenhouse ambient temperature (T_{gh}). Figure 6. illustrates the digester and the approximated location of the thermometers. T_{Min} and T_{Mout} were measured when the digester was loaded, and the digestate was pushed out by the entering slurry. Furthermore, Figure 7. presents the cross-section of the greenhouse and digester with detailed information on the thermometers' position.

As appreciated in Figure 7., the digester is located under and surrounded by several pots growing different vegetables such as aubergines, peppers and tomatoes. To obtain a representative greenhouse affecting the digester, T_{gh} was measured under the wooden structure, directly above the digester.

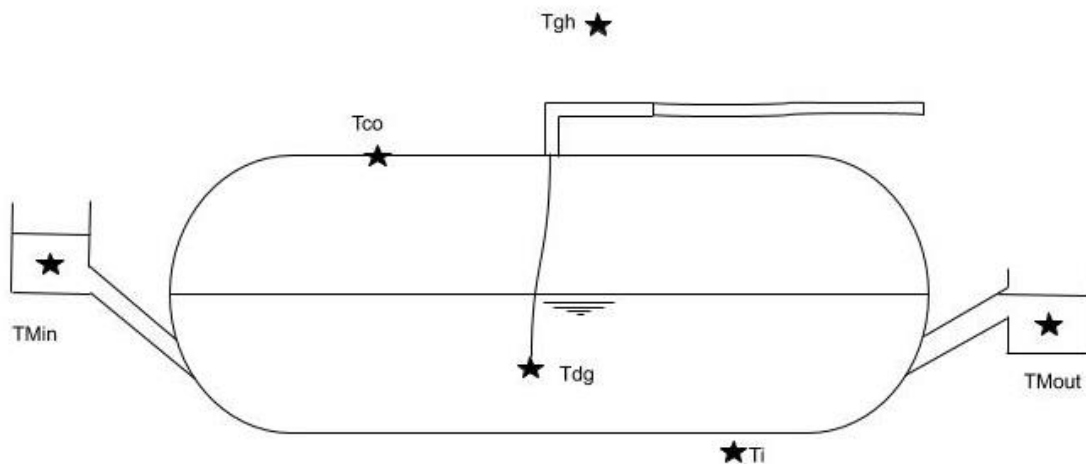


Figure 6. Elevation of the digester. Not to scale.

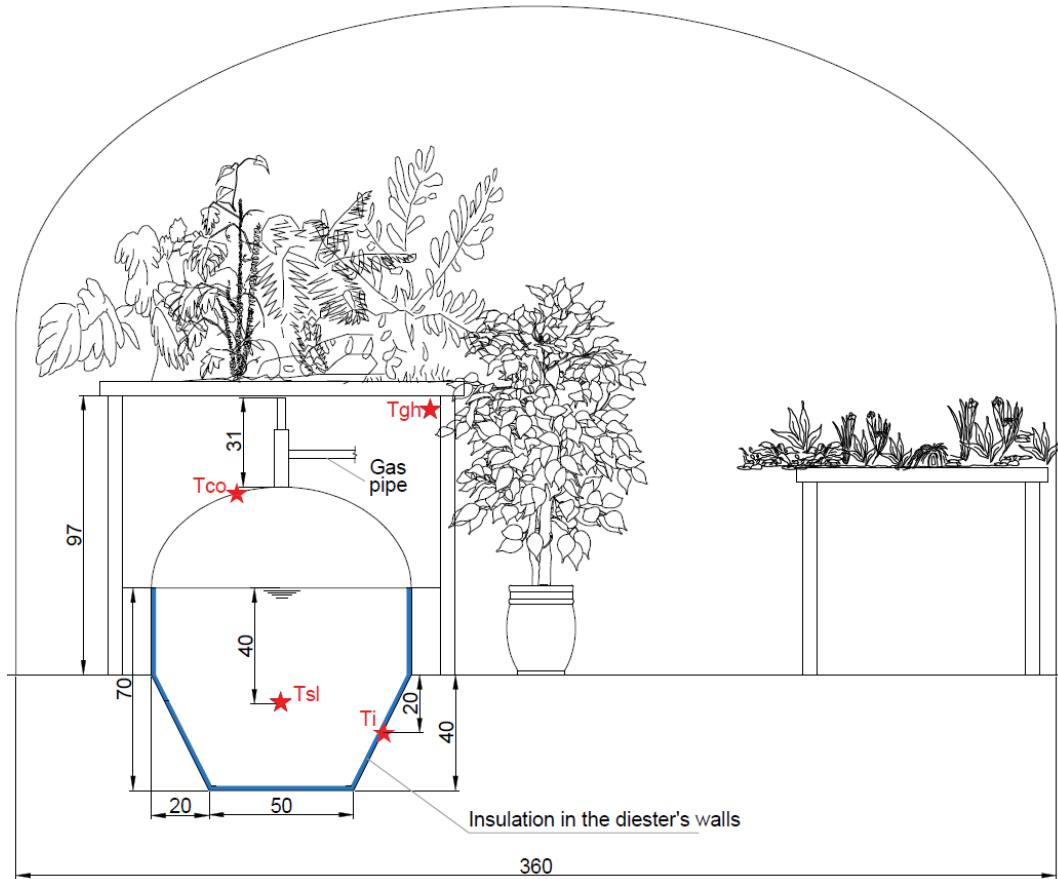


Figure 7. Detailed cross-section of the greenhouse and digester with thermometer locations. Expressed in cm.

3.1.1. Installation process

Since the digesters are designed and manufactured to be hermetic and maintain the biogas inside of it a modification of the biogas outlet cap was done. For the introduction of the probe inside the digester, the cap was removed and replaced rapidly with a plastic bag and rubber band to prevent the biogas from escaping. This process was done shortly after the gas was used and made sure that the digester had a minimum amount of gas inside and that any weight on top of it were removed. After it, a hole was drilled in the cap of the digester outlet and the probe measuring T_{dg} was introduced. To prevent any leak after installation, the perforation was then sealed using a silicone sealant that was left to curate overnight and tested with water and soap to make sure it was hermetic after its installation. Figure 8. shows the final result of the cap after it was installed back in the digester. Finally, to assure that the probe remains inside the slurry at all times, a fishing weight was attached to it, and 1.10 meters of cable was introduced as seen in Figure 7.

The installation of T_{co} and T_i . To measure T_{co} , a thermometer was taped to the surface of the digester using insulating tape. Finally, the second Extech TM20 thermometer was placed by slightly separating the digester from its ground insulation and introducing the probe 50 cm in the gap.



Figure 8. Extech TM20 Thermometer measuring the temperature inside the digester interior installed

3.1.2. Thermal model validation

The recordings obtained from the different sensors will provide insights on the effects that the ambient, slurry inlet and ground temperature have on the digestate inside the reactor. The data found will then be used to validate the digester thermal model constructed, explained in Section 4.1.

3.2. Biogas production

In order to develop the gas production model, a register of the loading of the digester was developed before starting taking temperature measurements. In the record, the volume of both manure and water added are registered. The information obtained is presented in Appendix 1. A black-box type model was developed, not taking into account the different chemical and biological reactions occurring inside of the digesters, to obtain a prediction of the biogas production using less specific variables (Lauwers *et al.*, 2013). The main goal of the model is to get an accurate production rate without involving the different complex biological processes occurring in AD but to associate the effects of

temperature in the process. Key feedstock characteristics such as volatile solids (VS) and biochemical methane potentials were taken from the literature and used as inputs as further discussed in Section 4.2.

In order to validate the biogas production model based on theoretical analysis, the real production of the digester was obtained using a previously installed low-pressure synthetic diaphragm gas meter, the BK-G4 meter (see Figure 9.), manufactured by Honeywell Elster (Elster, 2019) located before the stove used for domestic purposes in the farm. It is worth noticing that the aforementioned meter is not designed to measure biogas production, and it's considered as a source of error. However, the measurements will give an idea of the biogas production and the effects of temperature variations and loading rates.

Biogas production was calculated by closing the valves of the second digester and solely consuming the gas from the first reactor. The gas was used until the cover of the digester had dropped and reached the slurry surface. Additionally, to assure that the majority of the gas is consumed and the measurements are accurate, the measure was taken until the gas pressure exiting the stove has dropped and the flame was extinguished.



Figure 9. BK-G4 M gas meter.

4. Thermal and biogas production modelling

4.1. Thermal model

The proposed 0D model describes the heat transfer phenomena occurring in the slurry is developed using energy balance equations of the slurry following Figure 10. Also, the simulation includes the heat balance equations of the reactor exposed surface (co).

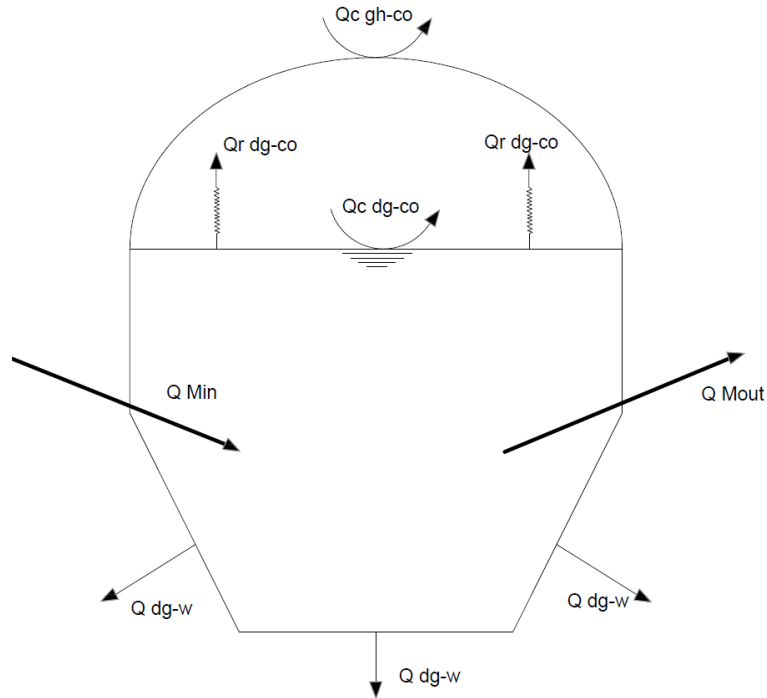


Figure 10. Heat transfer phenomena occurring in the biodigester.

As presented in Figure 10., five different heat flows are considered for the thermal analysis of the digestate: heat transfer through the digester's walls (w), convective and radiative from the reactor surface (co) and the effect of the slurry flows (Min and Mout). Applying the energy conservation principle, the digester analysis equation is as follow:

$$\rho_{dg} V_{dg} C_{dg} \frac{dT_{dg}}{dt} = Q_{Min} - Q_{r\ dg-co} - Q_{c\ dg-co} - Q_{dg-w} - Q_{Mout} \quad (4.1)$$

Where ρ represents density, V volume, C constant pressure heat capacity, T , temperature and t , time. Furthermore, Q_{Min-dg} , $Q_{dg-Mout}$ and Q_{dg-w} expresses the heat transfer in the digestate due to the influent feedstock, the effluent slurry and through the contact of the digestate with the digester's walls, respectively. Moreover, $Q_{r\ co-dg}$ and $Q_{c\ co-dg}$ represents the radiative and convective heat flux respectively between the

reactor's cover to the digestate. In contrast to the digestate, the reactor cover's heat capacity is neglected (Perrigault *et al.*, 2012); thus, its heat-balance equation is presented as follow:

$$0 = Q_{c\ gh-co} - Q_{r\ co-dg} - Q_{c\ co-dg} \quad (4.2.)$$

Assumptions:

- Each element in the model is represented to have a single temperature and kept constant throughout its entire geometry
- The biogas in the reactor is modelled as a rectangular prism calculated considering a completely inflated biodigester (Perrigault *et al.*, 2012)
- Physical properties of the slurry influent are considered equal to the digestate inside the digester (with the exception of temperature)
- The effects of solar radiation and the radiative heat transfer from the greenhouse to the reactor are neglected due to the protection that the plants surrounding the reactor provide (see Figure 7.)
- Long-wave radiations emitted from the cover to the atmosphere are neglected.
- Heat losses due to evaporation of water evaporation inside the digester and biogas flow are neglected (Kishore, 1989).

4.1.1. Modelling of the convective heat transfer from the greenhouse air (T_{gh}) to the digester cover (co), $Q_{c\ gh-co}$

The convective heat flux from the greenhouse air to the cover is given by (Lienhard IV & Lienhard V, 2017):

$$Q_{c\ gh-co} = h_{c\ gh-co} A_{co-gh} (T_{gh} - T_{co}) \quad (4.3)$$

Where A_{co-gh} is the area of the surface of the digester, $h_{c\ gh-co}$ is the convective heat transfer coefficient between the greenhouse and the digester and, T_{gh} and T_{co} are the greenhouse and digester's surface temperature, respectively. Free convection is assumed to take place in this situation because the polyethene greenhouse protects the digester from exposure to winds. The convective heat transfer coefficient is then obtained following Nusselt and Rayleigh numbers calculations. In the case of free convection on the upper surface of a hot plate or the lower surface of a cold plate ($T_{co} > T_{gh}$), the Nusselt number is calculated as follows (Lienhard IV & Lienhard V, 2017):

$$Nu = \frac{h_c gh-co L_c}{\lambda_{air}} = \begin{cases} 0.54 * Ra^{1/4} & \text{if } 2 * 10^4 \leq Ra \leq 8 * 10^6 \\ 0.15 * Ra^{1/3} & \text{if } 8 * 10^6 \leq Ra \leq 10^{11} \end{cases} \quad (4.4)$$

Where Ra is the Rayleigh number, Nu the Nusselt number, λ_{air} is the air's thermal conductivity ($Wm^{-1}K^{-1}$) and L_c (m) the reactor's surface characteristic length, calculated as a ratio of the digester's area and perimeter (modelled as a flat, rectangular plate) (Incropera *et al.*, 2007). Ra is calculated as follows:

$$Ra_{co-gh} = \frac{g\beta|\Delta T|L_c^3}{\nu_{air}^2} Pr_{air} \quad (4.5)$$

Where g is gravity, β is the thermal expansion coefficient (K^{-1}), calculated as $1/T$ (ideal gas assumption) (Hreiz *et al.*, 2017b), Pr_{air} is the air Prandtl number taken as 0.714 and ν_{air} the kinematic viscosity (m^2s^{-1}) evaluated at 11 °C. In the case of free convection in the upper surface of a cold plate ($T_{co} > T_{gh}$), the digester's surface gains heat from the surrounding air and in this case, the heat transfer coefficient is calculated as:

$$Nu = \frac{h_c gh-co L_c}{\lambda_{air}} = 0.27 * Ra^{1/4} \quad (4.6)$$

4.1.2. Modelling the radiative heat transfer between the digestate (dg) and the digester cover (co), $Q_{r co-dg}$

The radiative heat transfer between the digester and the slurry was modelled as one grey body enclosed by another. Considering that the slurry has a flat surface, the net heat transfer is calculated by (Lienhard IV & Lienhard V, 2017):

$$Q_{r co-dg} = \sigma \frac{T_{co}^4 - T_{dg}^4}{\frac{1 - \varepsilon_{co}}{\varepsilon_{co} A_{co-dg}} + \frac{1}{A_{co-dg}} + \frac{1 - \varepsilon_{dg}}{\varepsilon_{co} A_{dg-co}}} \quad (4.7)$$

Where σ is the Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$), ε_{co} and ε_{dg} are the thermal emissivity of the cover and digestate, respectively. Finally, A_{co-dg} and A_{dg-co} the areas of the inner surface of the cover and the surface of the slurry, respectively.

4.1.3. Modelling the convective heat transfer between the digestate (dg) and the cover (co), $Q_{c dg-co}$

The biogas between the cover and digestate can gain or lose heat and affects the surrounding surfaces. For the calculation of the heat flux between both elements, the biogas contained is modelled as a rectangular cavity with both horizontal surfaces at

different temperatures and with the vertical surfaces considered completely insulated (Incropera *et al.*, 2007). Moreover, for terms of simplicity, the biogas temperature is reviewed as the average between the cover and the slurry. Thus, the convective heat flux between the slurry and reactor is given by:

$$Q_{c\ dg-co} = h_{c\ dg-co} A_{dg-co} (T_{dg} - T_{co}) \quad (4.8)$$

For the calculation of $h_{c\ dg-co}$, the direction of the heat flux must be known. In the case of a flat surface heated from bellow ($T_{dg} > T_{co}$) the heat flux can be obtained by:

$$Nu = \frac{h_{c\ dg-co} L_{bg}}{\lambda_{bg}} = 0.27 * Ra^{1/4} \quad (4.9)$$

$$\text{With: } Ra_{sl-co} = \frac{g \beta_{bg} |T_{dg} - T_{co}| L_{bg}^3 Pr_{bg}}{v_{bg}^2} \quad (4.10)$$

Where β_{bg} is the biogas thermal expansion coefficient, calculated as $1/T_{bg}$ (assuming ideal gas due to the low working pressure). In contrast, in the situation where $T_{dg} < T_{co}$, the heat transfer flow is from top to bottom and is considered to occur by conduction (Nu=1) (Incropera *et al.*, 2007).

4.1.4. Modelling the heat transfer from the slurry (sl) to the digester's walls (w),

$$Q_{dg-w}$$

The slurry inside the digester insulated in the sidewalls and floor, as shown in Figure 7. Furthermore, the temperature between the digester walls and the insulation surrounding the reactor has been measured (T_i) and assumed constant through the floors and walls. The heat flow through the ground can be expressed in terms of effective conductance (Axaopoulos *et al.*, 2001) and is calculated using:

$$Q_{dg-w} = \frac{e_w}{\lambda_w} A_{w-i} (T_{dg} - T_i) \quad (4.11)$$

Being e_w the reactor bag width (m), λ_w , the reactor bag thermal conductivity and A_{w-i} the contact area between the digester walls and floor and, the insulation around it.

4.1.5. Modelling the heat transfer due to the manure flow, Q_{Min} and Q_{Mout}

The energy required for the influent slurry to reach the digester's working temperature and the energy lost due to the digesting exiting the reactor by overflow is given by:

$$Q_{\dot{m}} = \dot{m} C_w (T_{dg} - T_{Min}) \quad (4.12)$$

$Q_{\dot{m}}$ represents the heat flow occurring due to the mass flow (\dot{m}) in $\text{kg}\cdot\text{day}^{-1}$ of the slurry entering and leaving the reactor. Equation 4.12 describes the calculation of both Q_{Min} and Q_{Mout} . Moreover, the manure slurry has a similar heating capacity as water (Hreiz *et al.*, 2017a) and, for simplification purposes are assumed equal ($4.188 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, measured at $16 \text{ }^\circ\text{C}$).

4.1.6. Solving process

To solve the energy balance equation, an iterative (100 cycles) process is undertaken. First, the digester physical properties and geometry are entered. The physical properties of the digester were taken from Toyozawa *et al.* (2017). Second, T_{dg} is assumed and the real value of T_{gh} for a given time is used as input. Both values are then used to solve eq. 4.2. through iteration and obtain an initial value for the cover temperature (T_{CO}). With the new value for T_{CO} , and the recordings of T_{Mout} and T_{Min} , equation 4.1. is solved to find a final value for T_{dg} . The process repeats itself for every greenhouse temperature registered. The parameters and physical properties used for the model are presented in Table 2 (Hreiz *et al.*, 2017b; Toyozawa *et al.*, 2017).

Table 2. Physical parameters used for the thermal model

Parameter	Value	Unit
g	9.81	m/s^2
λ_{air}	0.025	$\text{W}/\text{m}\cdot\text{K}$
vair	1.40E-05	m^2/s
Prair	0.714	-----
vbg	1.50E-04	m^2/s
Prbg	0.75	-----
λ_{bg}	0.003	$\text{W}/\text{m}\cdot\text{K}$
ρ_{dg}	800	kg/m^3
Vdg	3.3	m^3
Cdg	4.1888	$\text{kJ}/\text{kg}\cdot\text{K}$
σ	5.67E-08	$\text{W}/\text{m}^2\cdot\text{K}^4$
ϵ_{sl}	0.8	-----
ϵ_{co}	0.9	-----
Aco	5.4	m^2
Adg	5.4	m^2
Pco	13.8	m
ew	0.0015	m
λ_w	0.33	$\text{W}/\text{m}\cdot\text{K}$
Aw-i	13.07	m^2

4.2. Biogas production model

As described in Section 2.2., biogas production through anaerobic digestion depends on several parameters. In addition to the ones previously discussed, an essential parameter for the calculation of the methane production rate is the dimensionless relative substrate-microorganisms kinetics parameter (K) of the system (Chen & Hashimoto, 1979). It is proven that K is dependent on the VS content (S_o) of the feedstock and increases exponentially as S_o increases and for cattle manure is given by (Hashimoto, 1982):

$$K = 0.8 + 0.0016e^{0.06S_o} \quad (4.13)$$

With S_o being the VS content in g/kg loaded mass. Moreover, the calculation for the daily rate of methane production is calculated following Chen & Hashimoto, (1979) proceedings:

$$\gamma_v = \frac{B_o S_o}{\theta} \left(1 - \frac{K}{\theta * \mu_m - 1 + K} \right) \quad (4.14)$$

Where γ_v is the daily volumetric methane production rate ($LCH_4 \text{ day}^{-1}m^{-3}$), θ the retention time (HRT) in days, B_o is the ultimate CH_4 yield as HRT approaches infinity ($L \text{ kg}^{-1} \text{ VS}$) and, μ_m is the specific microorganisms production rate (day^{-1}) described with the experimental results obtained by Hashimoto, Chen & Varel, (1981):

$$\mu_m = 0.013T - 0.129 \quad (4.15)$$

Where T is the digestate working temperature.

Moreover, Franzellin & Paw, (2015), found that the biogas produced by the digester had an average CH_4 content of 60.3%. Assuming this value, the daily biogas production rate is calculated by:

$$\gamma_{bg} = \frac{\gamma_v}{0.603} \quad (4.16)$$

Equations 4.13. and 4.16. will be used for each daily average working temperature of the digester. S_o and B_o of the influent slurry were assumed equal to the characteristics used by Pham, Triolo & Sommer, (2014), being 36 g kg^{-1} loaded mass and $200 \text{ L kg}^{-1} \text{ VS}$ respectively. However, it is worth noticing that both S_o and B_o values are heavily dependent on specific parameters such as age of the manure (fresh manure have higher B_o), animal age, food provided to the cattle and ambient temperature (Hashimoto, 1982;

Hashimoto, Varel & Chen, 1981). Details on the HRT used for the calculation are explained in Section 5.2.

5. Results and discussion

5.1. Thermal analysis

This section presents the results obtained during the thermal study of the digester and from the temperature readings. Figure 11. Illustrates the temperatures registered for T_{dg} , T_{gh} , T_{co} and T_i . Temperatures for T_{Min} and T_{Mout} are not included in Figure 11., as only occasional readings were taken when the digester was loaded. Temperature readings for obtained are presented for T_{dg} , T_{gh} , T_{co} and T_i in Appendix 2.

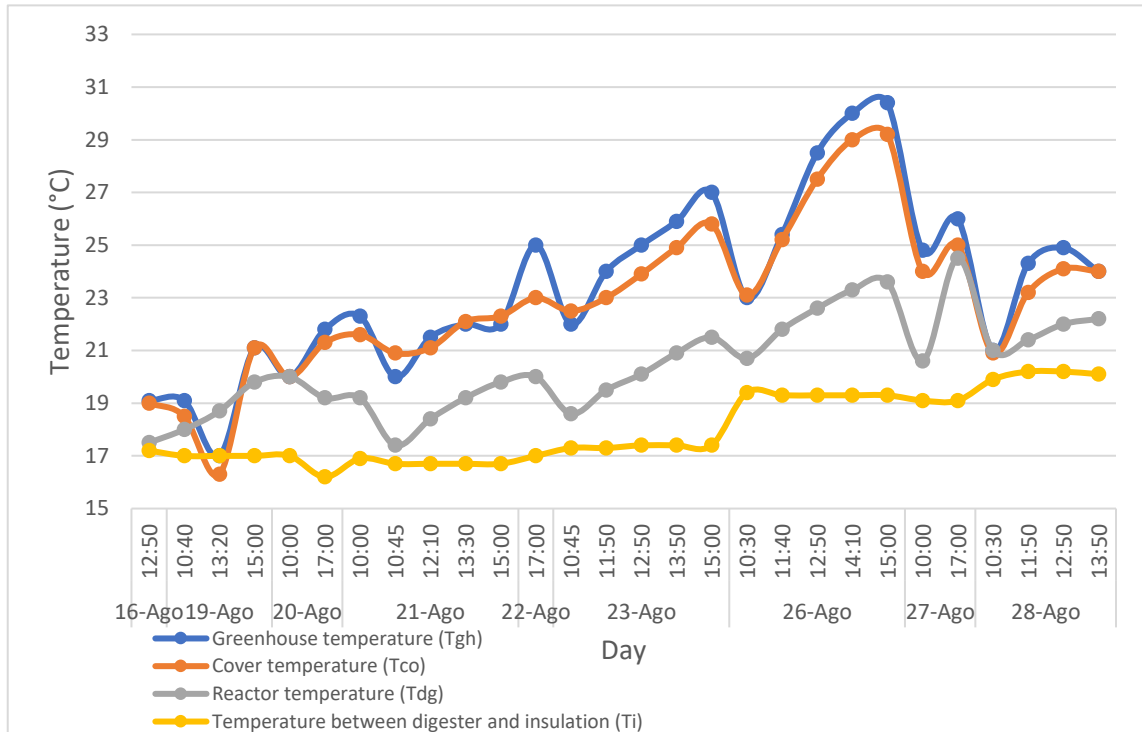


Figure 11. Temperatures registered

It can be observed that T_{gh} and T_{co} are closely related as expected, being the greenhouse temperature slightly higher than the digester cover temperature. Moreover, it is also appreciated that T_{dg} follows a similar trend compared to both temperatures. However, it can also be observed that T_{dg} has several disturbances that impede it from following the trend set by T_{gh} . The vegetables and its structure surrounding the biodigester protects it from direct sunlight, and solar irradiation has little effect on the reactor, causing a temperature difference of up to 6°C between shaded areas and the rest of the greenhouse. The reason for this disturbance is because of the nearly constant temperature between the insulation and the biodigester and due to the heat entering and leaving the digester when loaded. The average temperature observed for the digester

during the study is 20.15 °C, which, as discussed in Section 2.2.1. is in the limit between psychrophilic and mesophilic conditions. Moreover, the average reactor temperature is significantly less than that predicted by Toyozawa et al., (2015) who estimated average temperature of approximately 40 °C for the same reactor in August. The difference in design vs real working conditions has significant negative impact on biogas production as explained in Section 5.2.

It is worth noticing that T_i maintained at a nearly constant temperature throughout the study and is not heavily influenced by daily temperature changes occurring around the biodigester. This behaviour illustrates the high thermal inertia that the combination of insulation and soil has. The surrounding soil thermal inertia limits temperature variability and acts as insulation from the elements (Cheruy et al., 2017). The effects of the surrounding soil to the insulation and digester temperatures have to be further studied during winter to analyse if then acts as a source of heat. It can also be appreciated that between 23/08 and 26/08 a sudden increase of around 2 °C in T_i is observed. In order to understand the temperature increase in T_i , Figure 12. presents the ambient temperatures of the Southwark Council (where the farm is located) during the study. A rise of 3°C and 5 °C for minimum and maximum temperatures, respectively is observed between 24/08 and 26/08 which is accounted for the average temperature rise of the system. Furthermore, a second increase in T_i is observed. The reason for in this second increase may be accounted to the average increase of the digester working temperature and the effect it has on the insulation.

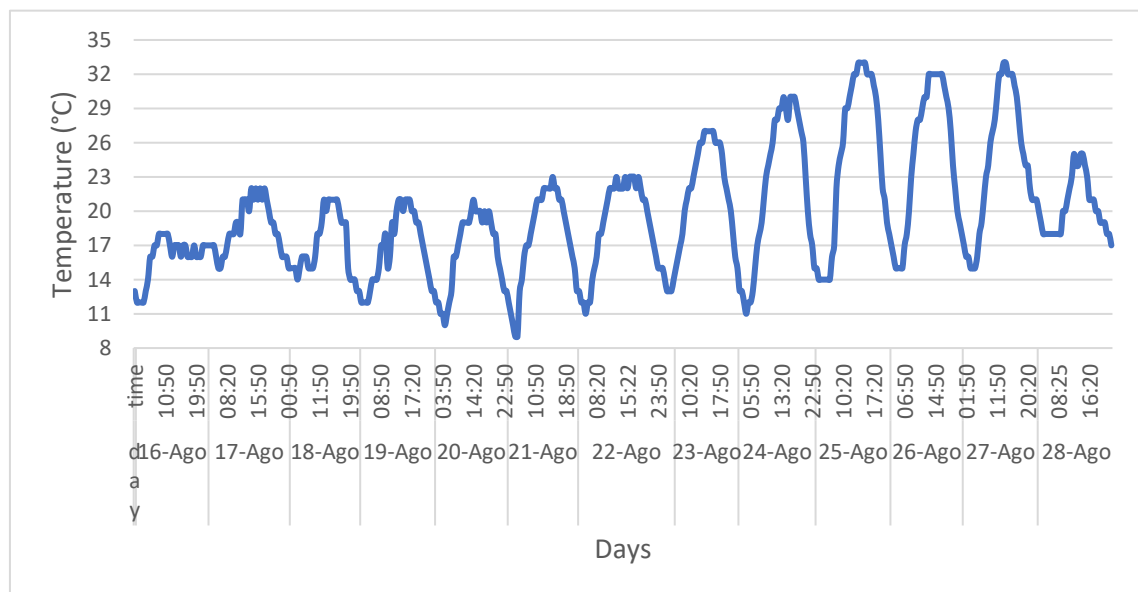


Figure 12. Southwark Council temperatures (Timeanddate.com, 2019).

Figure 13. presents the correlation between T_{dg} and T_{gh} . For greenhouse temperatures lower than 18 °C it is observed that T_{gh} reduces temperature at a higher rate than T_{dg} and eventually becomes lower than T_{dg} . In contrast, for higher greenhouse temperatures, T_{dg} is significantly lower than T_{gh} . This result contradicts the findings of Garfi et al., (2011) and Perrigault et al., (2012) who observed that the slurry inside the digester was 2.1 °C and 8.5 °C, respectively higher than the greenhouse temperature. There are several possible reasons for this contrast. As aforementioned, the plants cover the digester from solar radiation, reducing a potential heat gain (especially during summer months); moreover, the digester roof is damaged, allowing rainwater to reach the digester. Also, the greenhouse is often opened, so that volunteers and staff can water the plants exposing the digester to winds and cold water.

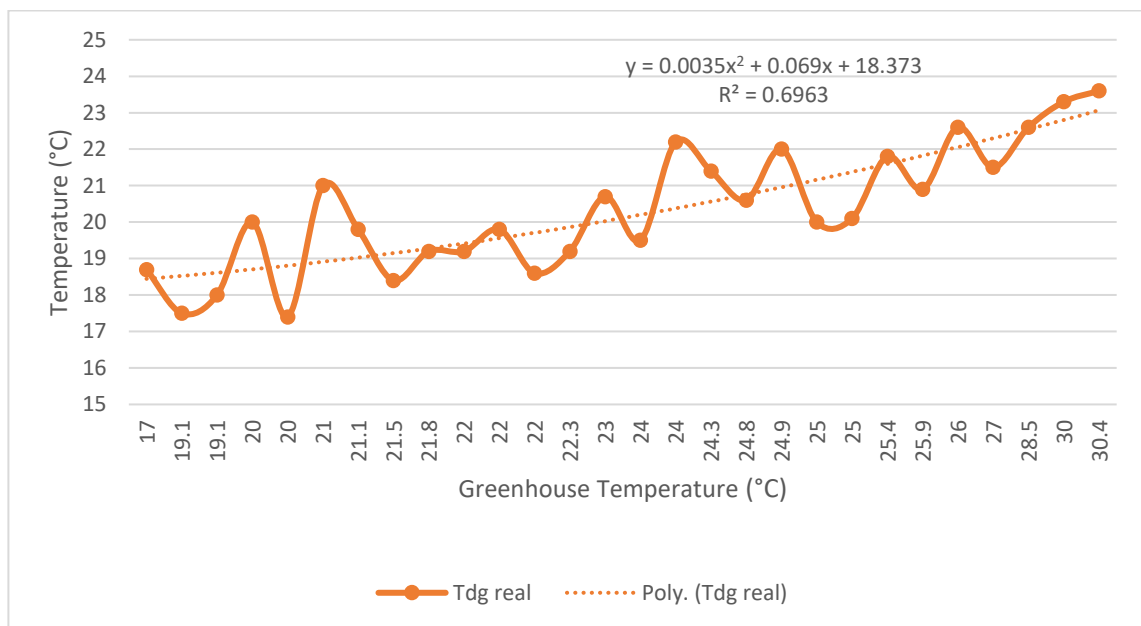


Figure 13. Correlation between T_{gh} and T_{dg} .

The modelled digester temperature vs the real working temperature are shown in Figure 14, and the results of the model are presented in Appendix 2. It can be seen that the modelled temperature follows the same trend as the real readings obtained during the study. Moreover, the model has an accuracy of $1.66 \text{ °C} \pm 0.18$ which is 8.24% of the average working temperature presented in the digester.

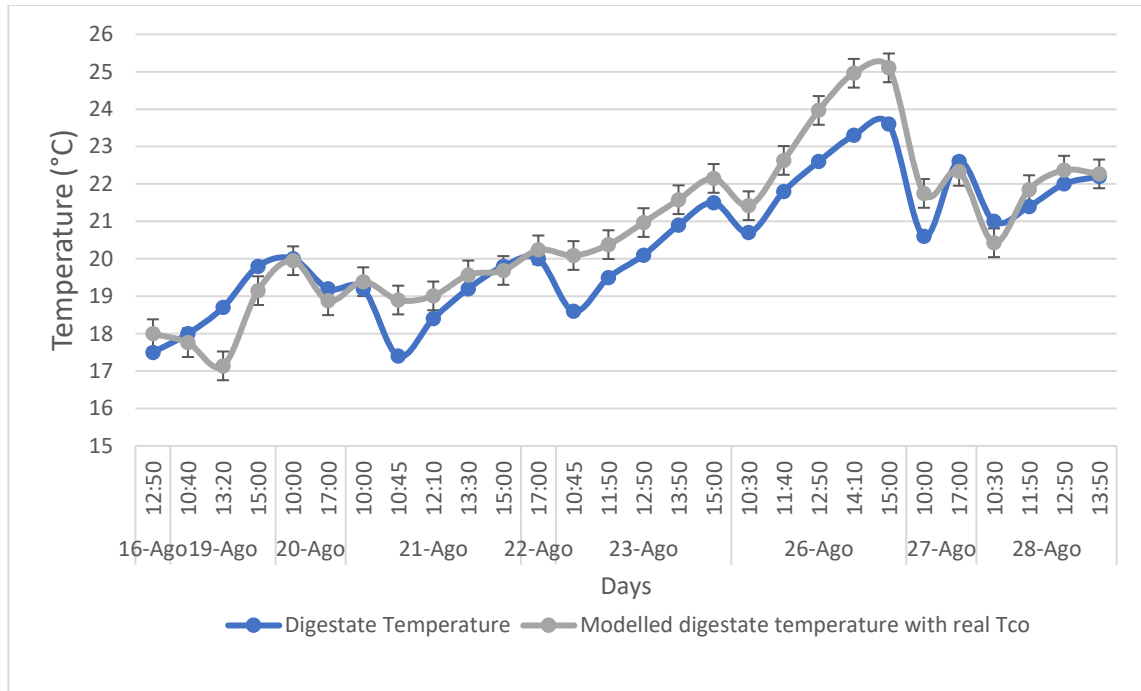


Figure 14. Real T_{dg} vs. Modelled T_{dg}

The model can improve its accuracy if more thermometers are installed with a data logger to record temperature more frequently and in a more controlled manner. For a reactor of the dimensions studied, 15 thermometers will provide the necessary information for precise modelling. Six thermometers in the slurry, placed in three columns 10 and 90 centimetres under the slurry surface, separated 1.5 meters between each column. Four placed between the insulation and the digester (two on each of the longer sides). Three more in the digester surface. One to measure the gas temperature. Finally, the last two for the input and effluent slurry.

As appreciated from Table 3., the readings of T_{Mout} have been obtained with a less frequency than T_{Min} . Although the influent slurry should push the digestate out of the reactor at the moment it is being loaded, in reality, the digestate not always exited the digester at the same time it was being loaded. This can be explained because the output end of the digester is not restricted by soil. Also, due to the flexible characteristic of the digester bag, apparently the digestate was able to accommodate itself inside and did not leave at the expected moment. It seems that in such cases, the biol exited afterwards when the gas pressure inside the reactor started to build up and pushed the slurry out.

Table 3. Influent and effluent temperatures

Day	Time	Manure influent temperature (T_{Min}) (°C)	Manure effluent temperature (T_{Mout}) (°C)
7-Ago	16:45	21.20	
8-Ago	16:00	21.50	
9-Ago	17:00	22.60	
12-Ago	17:00	17.20	16.30
14-Ago	16:30	16.90	
20-Ago	10:00	17.00	16.30
21-Ago	10:00	16.00	
22-Ago	17:00	20.10	16.90
27-Ago	10:00	21.50	19.10
28-Ago	13:00	22.50	19.20

Moreover, the effluent temperature obtained is on average 2.5 °C less than T_{dg} . The main reason for this important temperature difference between the centre of the digester and the effluent is because, in addition to the absence of soil in its surroundings, it is poorly insulated. Furthermore, the effluent end is not located inside the greenhouse, leaving that end exposed to rain and wind.

The influent temperature caused an interesting behaviour in the digestate temperature. In 16/08 the digester was loaded with a slurry temperature of 16 °C at 10:00 am after measuring T_{dg} which presented a temperature of 19.2 °C. Forty-five minutes later, T_{dg} was measured again and on this occasion, it had dropped 1.8°C. Moreover, in 28/8, the digester was loaded with a T_{Min} of 22.5 °C when T_{dg} was at 22°C. One hour later, T_{dg} was measured again and even though T_{gh} , T_{co} and T_i had dropped during the hour, T_{dg} rose 0.2 °C. Unfortunately, this phenomenon could not be further studied due to time constraints and because the digester was mainly loaded at the farm's closing hours.

5.2. Biogas production

Besides the several aspects affecting biogas composition and production, a tailored design, considering the exact working conditions, type of organic waste to be treated and its availability are essential for appropriate performance. The digester studied was originally designed to use primarily swine waste as a feedstock with a manure to water ratio of 1:4. Furthermore, it was recommended that the biodigester should work with a retention time of 35 and 45 days for summer and winter months, respectively (Toyozaawa et al., 2017). However, during the study it was found that these parameters were not followed. Cow dung was primarily used when loading the digester, but due to manure availability constraints, it was also mixed with swine waste when needed. The loading of the digester was not effectuated on a daily basis, but arbitrarily according to manure availability. The digester loading register is presented in Appendix 1. The digester was loaded with a total of 400 litres of manure in 21 days. According to equation 4., the working OLR is calculated as:

$$OLR \left(\frac{L}{day} \right) = \frac{400 (L)}{21 (days)} = 19 L/day$$

Furthermore, a total of 720 litres of water were added to the mixture, resulting in a manure to water ratio of 1:1.8, less than half of the recommended value. However, when installing the thermometer inside the digester and by observing the effluent, it could be appreciated that there were no signs of a top scum layer affecting the flow of the digestate. Nevertheless, it meant that the HRT did not comply with the design value. Therefore, real HRT is calculated using equation 3.:

$$HRT (day) = \frac{3300 L}{53 \left(\frac{L}{day} \right)} = 62 days$$

In practice, the real HRT nearly doubled the designed retention time. Furthermore, HRT represents the precise time required for the organic matter to be fully degraded. When the retention time is exceeded, the already degraded organic matter does not produce gas at the desired rate and accumulates suspended solids in the digester occupying space that fresh manure could occupy. Therefore, the biodigester does not operate at maximum efficiency.

Figure 14. presents the biogas production model results and its correlation with average working temperatures. The graph shows the dependency that gas production has with the working temperature. The model yielded a total of 6748 litres of gas, averaging an approximate of 563 litres daily. In contrast, the real gas production obtained was of 4760 litres. Results of the gas production model are displayed in Appendix 3

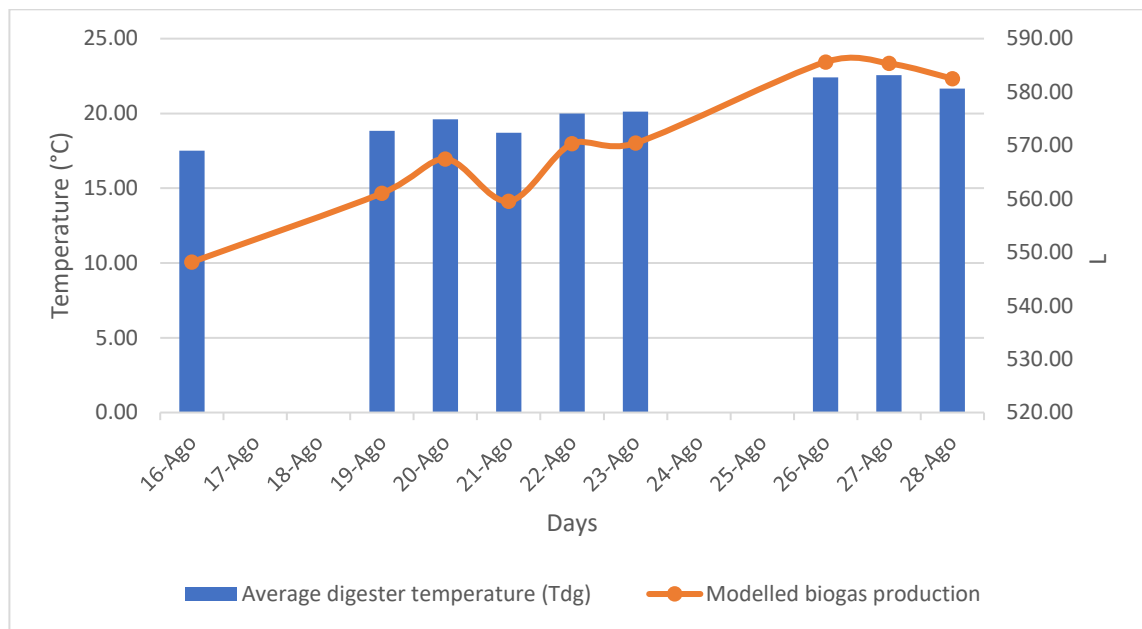


Figure 15. Biogas daily production vs average greenhouse temperature

The difference of nearly 2m³ can be explained because the digester experiences significant daily temperatures variations, fluctuating between the psychrophilic and mesophilic regime. As discussed in Section 2.2.1, methanogenic bacteria are highly sensitive to temperature changes, and the observed variations affect it negatively. Furthermore, the feedstock parameters used for the model are not representative of the manure obtained on the farm because the ultimate methane yield is highly dependent on site-specific characteristics as discussed. Moreover, accumulation of suspended solids resulting from not adhering to design parameters, affects the biogas yield of the system.

6. Sources of Error

- Due to limitations in the timeline of the project, two Extech TM20 digital thermometers were used to measure T_{dg} and T_i . However, two analogue thermometers were used for measuring T_{co} and T_{gh} with a precision level of a unit. The decimals of T_{co} and T_{gh} were obtained visually.
- The two Extech TM20 digital thermometer has an accuracy of ± 0.5 °C in the range between 0 °C to 24 °C (Extech, Instruments, 2019).
- Due to logistics constraints, a data logger could not be purchased and only spot checks during working hours (10 am - 5 pm) could be registered. Temperature readings out of this schedule could not be obtained, meaning that overnight and weekend readings are not included in the thermal analysis.
- The loading register is filled by farm staff, which calculated both water and manure volumes in terms of bucket size.
- The digester works mostly with cattle manure, however, in two occasions was loaded with an uncertain amount of pig manure. Pig manure has different properties than cattle waste, and it can affect gas production.
- Feedstock characteristics are taken from literature using cattle manure. As discussed in section 4.2., physical parameters are site-specific and thus can create discrepancies between the gas production model and the results.
- The digester's insulation is damaged in the influent and effluent areas, causing an increase in the thermal sensitivity of both ends as compared to the main body of the slurry. This is caused naturally by the '*wear and tear*' effect due to the loading process and maintenance of the digestate pump in the effluent bucket.
- The temperature throughout the digester, greenhouse and digestate are assumed constant for the thermal model.
- Solar radiation is neglected in the thermal model because of the plants surrounding the digester. However, the digester is not equally covered in throughout its extension.
- Every day volunteers entered the greenhouse to water the plants on top of the digester, which also reached the digester affecting its temperature.

7. Concluding remarks

7.1. Conclusions

The main goal of this research was to obtain insights on the thermal performance of a small-scale anaerobic digester subjected to psychrophilic and mesophilic conditions and its effect on biogas production. It was found that the digester did not take full advantage of the greenhouse because of the plants surrounding the digester. Shade and moisture provided by vegetables reduced the ambient temperature near the digester by 6 °C. Moreover, it was found that the digester temperature fluctuates through the mesophilic and thermophilic regime on a daily basis. Also, it presented a maximum daily temperature fluctuation of 3°C which severely affects the performance of the digester. In addition, the thermal model developed described the thermic behaviour of the digestate with an accuracy of 1.66 °C.

It was found that the studied digester is oversized for the manure availability of the farm as it failed to produce enough to feed the digester with the designed loading rates and retention times, reducing the efficiency of the system. The final gas production obtained is 4760 liters which is significantly less than the value obtained by the gas production model with nearly 2 m³ of difference.

7.2. Recommendations for future work

This project provided insights on directions to follow for future research regarding monitoring of the thermal efficiency and gas production of low-cost anaerobic digesters. One major limitation faced by the research was the lack of constant information regarding both the temperature of the digester and the daily biogas production. First, in order to improve the monitoring of the thermal phenomena occurring in the digester, fifteen thermometers coupled with data loggers should be implemented. This addition will help to further understand the heat flux in the system and give insights on how to improve its performance. Furthermore, continuous information regarding the ambient temperature will increase the accuracy for predicting working conditions. Moreover, the installation of a biogas-specific meter to be placed in the biogas outlet is essential to give an accurate correlation between the effects of temperature and gas production.

For future design and installation of low cost, small-scale anaerobic digesters facing psychrophilic conditions, it is essential to consider all the possible passive heating options and manage the space correctly. The digester's heat gain should be prioritised; otherwise, it will not perform as expected.

Finally, prior to the design of the digester, a thorough study regarding manure availability and its characteristics have to be undertaken. Knowing and predicting these details would significantly improve the quality of the design and its monitoring. Constant loading rates would facilitate the comparison with literature and reduce the number of variables to analyse in case of disruption of the system or change in the working conditions.

References

- Achinas, S. & Euverink, G.J.W. (2016) Theoretical analysis of biogas potential prediction from agricultural waste. *Resource-Efficient Technologies*. [Online] 2 (3), 143–147. Available from: doi:10.1016/j.reffit.2016.08.001.
- Appels, L., Baeyens, J., Degrève, J. & Dewil, R. (2008) Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science*. [Online]. Available from: doi:10.1016/j.pecs.2008.06.002.
- Armar-Klimesu, M. (2000) Urban agriculture and food security, nutrition and health. In: *Growing cities, growing food: urban agriculture on the policy agenda. A reader on urban agriculture*. p.
- Axaopoulos, P., Panagakis, P., Tsavdaris, A. & Georgakakis, D. (2001) Simulation and experimental performance of a solar heated Anaerobic digester. *Solar Energy*. [Online] 70 (2), 155–164. Available from: doi:10.1016/S0038-092X(00)00130-4.
- Azunre, G.A., Amponsah, O., Peprah, C., Takyi, S.A., et al. (2019) A review of the role of urban agriculture in the sustainable city discourse. *Cities*. [Online] Available from: doi:10.1016/j.cities.2019.04.006.
- Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V, et al. (2002) The IWA Anaerobic Digestion Model No 1 (ADM1). *Water science and technology: a journal of the International Association on Water Pollution Research*. [Online] 45 (10), 65–73. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/12188579>.
- Börjesson, P. & Mattiasson, B. (2008) Biogas as a resource-efficient vehicle fuel. *Trends in Biotechnology*. [Online] Available from: doi:10.1016/j.tibtech.2007.09.007.
- Bouallagui, H., Haouari, O., Touhami, Y., Ben Cheikh, R., et al. (2004) Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste. *Process Biochemistry*. [Online] 39 (12), 2143–2148. Available from: doi:10.1016/j.procbio.2003.11.022.
- Brown, K.H. & Jameton, A.L. (2000) Public health implications of urban agriculture. *Journal of Public Health Policy*. [Online] Available from: doi:10.2307/3343472.
- Bruce, A. Baudoin, R. Fu, X. Gisborn, D. Isven, C. & McGillivray, J. (2014). *Surrey Docks Farm Anaerobic Digestion: System Design*. (April).

Bryld, E. (2003) Potentials, problems, and policy implications for urban agriculture in developing countries. *Agriculture and Human Values*. [Online] Available from: doi:10.1023/A:1022464607153.

Buswell, A.M. & Mueller, H.F. (1952) Mechanism of Methane Fermentation. *Industrial & Engineering Chemistry*. [Online] 44 (3), 550–552. Available from: doi:10.1021/ie50507a033.

Buysman, E. (2009) *Anaerobic Digestion for Developing Countries with Cold Climates - Utilizing solar heat to address technical challenges and facilitating dissemination through the use of carbon finance*. [Online] (July), 1–165. Available from: doi:10.13140/RG.2.1.4848.8807.

Chae, K.J., Jang, A., Yim, S.K. & Kim, I.S. (2008) The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. *Bioresource Technology*. [Online] 99 (1), 1–6. Available from: doi:10.1016/j.biortech.2006.11.063.

Chen, J.L., Ortiz, R., Steele, T.W.J. & Stuckey, D.C. (2014) Toxicants inhibiting anaerobic digestion: A review. *Biotechnology Advances*. [Online]. Available from: doi:10.1016/j.biotechadv.2014.10.005.

Chen, Y.R. & Hashimoto, A.G. (1979) Kinetics of methane fermentation. *Biotechnology Bioengineering Symposium*.

Cheruy, F., Dufresne, J.L., Ait Mesbah, S., Grandpeix, J.Y. and Wang, F., 2017, April. Role of the Soil Thermal Inertia in the short term variability of the surface temperature and consequences for the soil-moisture temperature feedback. In EGU General Assembly Conference Abstracts (Vol. 19, p. 17983).

Dioha, I.J., Ikeme, C., Nafi, T., Soba, N.I., et al. (2013) Effect of Carbon To Nitrogen Ratio on Biogas Production. *International Research Journal of Natural Sciences*. 1 (3), 1–10.

El-Mashad, H.M., Van Loon, W.K.P. & Zeeman, G. (2003) A model of solar energy utilisation in the anaerobic digestion of cattle manure. *Biosystems Engineering*. [Online] Available from: doi:10.1016/S1537-5110(02)00245-3.

Elster, SE. (2019). Honeywell Elster - Product details - Product Catalog - Connected Utility. [online] Elster-americanmeter.com. Available at:

https://www.elsteramericanmeter.com/en/productdetails/164/en/BKG4_Meter?fid=4D7D31767CD542AE8B7FF016AEB6ADCF#sbox0=; [Accessed 19 Aug. 2019].

FAO (2003) The informal food sector: Municipal support policies for operators. *Food in cities collection*.

Ferrer, I., Garfí, M., Uggetti, E., Ferrer-Martí, L., et al. (2011) Biogas production in low-cost household digesters at the Peruvian Andes. *Biomass and Bioenergy*. [Online] 35 (5), 1668–1674. Available from: doi:10.1016/j.biombioe.2010.12.036.

Florides, G. & Kalogirou, S. (2007) Ground heat exchangers-A review of systems, models and applications. *Renewable Energy*. [Online]. Available from: doi:10.1016/j.renene.2006.12.014.

Franzellin, C. & Paw, A. (2015). Monitoring of a small scale anaerobic digester in an urban farm in London. Third Year Research Project.

Garfí, M., Ferrer-Martí, L., Perez, I., Flotats, X., et al. (2011) Codigestion of cow and guinea pig manure in low-cost tubular digesters at high altitude. *Ecological Engineering*. [Online] 37 (12), 2066–2070. Available from: doi:10.1016/j.ecoleng.2011.08.018.

Gray, M. (2016). Sterilization of Effluent from an anaerobic digester using novel methods.

Hashimoto, A.G. (1982) Methane from cattle waste: Effects of temperature, hydraulic retention time, and influent substrate concentration on kinetic parameter (k). *Biotechnology and Bioengineering*. [Online] 24 (9), 2039–2052. Available from: doi:10.1002/bit.260240911.

Hashimoto, A.G., Chen, Y.R. & Varel, V.H. (1981) *THEORETICAL ASPECTS OF METHANE PRODUCTION: STATE-OF-THE-ART*. In: 1981 p.

Hashimoto, A.G., Varel, V.H. & Chen, Y.R. (1981) Ultimate methane yield from beef cattle manure: Effect of temperature, ration constituents, antibiotics and manure age. *Agricultural Wastes*. [Online] Available from: doi:10.1016/0141-4607(81)90011-1.

Hreiz, R., Adouani, N., Fünfschilling, D., Marchal, P., et al. (2017a) Rheological characterization of raw and anaerobically digested cow slurry. *Chemical Engineering Research and Design*. [Online] Available from: doi:10.1016/j.cherd.2017.01.005.

Hreiz, R., Adouani, N., Jannot, Y. & Pons, M.N. (2017b) Modeling and simulation of heat

transfer phenomena in a semi-buried anaerobic digester. *Chemical Engineering Research and Design*. [Online] 119, 101–116. Available from: doi:10.1016/j.cherd.2017.01.007.

Incropera, F.P., DeWitt, D.P., Bergman, T.L. & Lavine, A.S. (2007) *Fundamentals of Heat and Mass Transfer 6th Edition*. [Online]. Available from: doi:10.1016/j.applthermaleng.2011.03.022.

K. G. Gebremedhin, B. Wu, C. Gooch, P. Wright, et al. (2005) Heat Transfer Model for Plug-Flow Anaerobic Digesters. *Transactions of the ASAE*. [Online] 48 (2), 777–785. Available from: doi:10.13031/2013.18320.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T., et al. (2011) The anaerobic digestion of solid organic waste. *Waste Management*. [Online]. Available from: doi:10.1016/j.wasman.2011.03.021.

Kishor, J., Goyal, I.C., Sawhney, R.L., Singh, S.P., et al. (1988) Solar assisted biogas plants III: Energy balance of fixed dome biogas plants and enhancement of production in winters. *International Journal of Energy Research*. [Online] Available from: doi:10.1002/er.4440120411.

Kishore, V.V.N. (1989) A heat-transfer analysis of fixed-dome biogas plants. *Biological Wastes*. [Online] 30 (3), 199–215. Available from: doi:10.1016/0269-7483(89)90121-3.

Kocar, G. & Eryasar, A. (2007) An application of solar energy storage in the gas: Solar heated biogas plants. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. [Online] Available from: doi:10.1080/00908310600626598.

Lauwers, J., Appels, L., Thompson, I.P., Degève, J., et al. (2013) Mathematical modelling of anaerobic digestion of biomass and waste: Power and limitations. *Progress in Energy and Combustion Science*. [Online] 39 (4), 383–402. Available from: doi:10.1016/j.pecs.2013.03.003.

Lettinga, G., Rebac, S. & Zeeman, G. (2001) Challenge of psychrophilic anaerobic wastewater treatment. *Trends in Biotechnology*. [Online]. Available from: doi:10.1016/S0167-7799(01)01701-2.

Lienhard IV, J.H. & Lienhard V, J.H. (2017) A HEAT TRANSFER TEXTBOOK, fourth edition. *Phlogiston Press*. [Online] Available from: doi:978-04864793161.

- Van Lier, J.B., Rebac, S. & Lettinga, G. (1997) High-rate anaerobic wastewater treatment under psychrophilic and thermophilic conditions. In: *Water Science and Technology*. [Online]. 1997 p. Available from: doi:10.1016/S0273-1223(97)00202-3.
- Liu, C. fang, Yuan, X. zhong, Zeng, G. ming, Li, W. wei, et al. (2008) Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. *Bioresource Technology*. [Online] Available from: doi:10.1016/j.biortech.2007.01.013.
- Mann, K. (2014) *Start-up and Performance Testing of an Innovative Biodigester Model on an Urban Farm*. (September).
- Metoffice.gov.uk. (2019). *Heathrow station historic data*. [online] Available at: <https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/heathrowdata.txt> [Accessed 26 Jul. 2019].
- Misra, R.V., Roy, R.N. & Hiraoka, H. (2003) On-farm Composting Methods. *Land and Water Discussion Paper*. [Online] Available from: doi:10.1017/CBO9781107415324.004.
- Nguyen, H. H. (2014). Modelling of food waste digestion using ADM1 integrated with Aspen Plus (Doctoral dissertation, University of Southampton).
- Ozturk, B. (2012) Evaluation of Biogas Production Yields of Different Waste Materials. *Earth Science Research*. [Online] 2 (1). Available from: doi:10.5539/esr.v2n1p165.
- Perrigault, T., Weatherford, V., Martí-Herrero, J. & Poggio, D. (2012) Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. *Bioresource Technology*. [Online] 124, 259–268. Available from: doi:10.1016/j.biortech.2012.08.019.
- Pham, C.H., Triolo, J.M. & Sommer, S.G. (2014) Predicting methane production in simple and unheated biogas digesters at low temperatures. *Applied Energy*. [Online] 136, 1–6. Available from: doi:10.1016/j.apenergy.2014.08.057.
- Poggio, D., Ferrer, I., Batet, L. & Velo, E. (2009a) Adaptación de biodigestores tubulares de plástico a climas fríos. *Livestock Research for Rural Development*. 21 (9).
- Poggio, D., Paiva Prado, M., Ferrer, I. & Velo, E. (2009b) Biodigestores de bajo coste para climas andinos. *Revista Brasileira de Agroecologia*. [Online] 4 (2), 4508–4511. Available from: <http://upcommons.upc.edu/handle/2117/7163>.

Poggio, D., Walker, M., Nimmo, W., Ma, L., et al. (2016) Modelling the anaerobic digestion of solid organic waste - Substrate characterisation method for ADM1 using a combined biochemical and kinetic parameter estimation approach. *Waste Management*. [Online] Available from: doi:10.1016/j.wasman.2016.04.024.

Rebac, S., Ruskova, J., Gerbens, S., van Lier, J.B., et al. (1995) High-rate anaerobic treatment of wastewater under psychrophilic conditions. *Journal of Fermentation and Bioengineering*. [Online] Available from: doi:10.1016/0922-338X(96)80926-3.

Singh, D., Singh, K.K. & Bansal, N.K. (1985) Heat loss reduction from the gas holder/fixed gas dome of a community-size biogas plant. *International Journal of Energy Research*. [Online] 9 (4), 417–430. Available from: doi:10.1002/er.4440090405.

Sistema.bio. (2019). *Sistema.bio - The biodigester solution*. [online] Available at: <https://sistema.bio/mx/> [Accessed 16 Aug. 2019].

Steinhauser, A. & Deublein, D. (2011) *Biomass to Biofuels Nanotechnology for the Energy Challenge Biofuels Catalysis for Renewables Energy Demand and Climate Change*.

Surendra, K.C., Takara, D., Jasinski, J. & Kumar Khanal, S. (2013) Household anaerobic digester for bioenergy production in developing countries: Opportunities and challenges. *Environmental Technology (United Kingdom)*. [Online] Available from: doi:10.1080/09593330.2013.824012.

Surrey Docks Farm London. (2019). *Surrey Docks City Farm - London*. [online] Available at: <https://www.surreydocksfarm.org.uk> [Accessed 24 Aug. 2019].

Timeanddate.com. (2019). *Past Weather in Southwark, England, United Kingdom — Yesterday or Further Back*. [online] Available at: <https://www.timeanddate.com/weather/@2637299/historic> [Accessed 29 Aug. 2019].

Toyozawa, H., Cheah, MH., & Jimenez, D. (2017). Design Report of the installation of an Anaerobic Digester at Surrey Docks Farm.

Turkdogan-Aydinol, F.I. & Yetilmezsoy, K. (2010) A fuzzy-logic-based model to predict biogas and methane production rates in a pilot-scale mesophilic UASB reactor treating molasses wastewater. *Journal of Hazardous Materials*. [Online] Available from: doi:10.1016/j.jhazmat.2010.06.054.

Wellinger, A., (1999). Process design of agricultural digesters. Publication Nova Energie GmbH.

Wellinger, A., Murphy, J. & Baxter, D. (2013) *The biogas handbook*. [Online]. Available from: doi:10.1533/9780857097415.

Xu, F., Li, Y. & Wang, Z.W. (2015) Mathematical modeling of solid-state anaerobic digestion. *Progress in Energy and Combustion Science*. [Online] 51, 49–66. Available from: doi:10.1016/j.pecs.2015.09.001.

Appendix 1. Digester Loading register

Day	Time	Animal origin	Manure volume (L)	Water added (L)	T_{Min} (°C)	T_{Mout} (°C)
7-Ago	16:45	Cow	20.00	60.00	21.20	
8-Ago	16:00	Cow	15.00	60.00	21.50	
9-Ago	17:00	Cow	20.00	60.00	22.60	
12-Ago	17:00	Cow	30.00	60.00	17.20	16.30
14-Ago	16:30	Cow+pig	45.00	60.00	16.90	
20-Ago	10:00	Cow	75.00	105.00	17.00	16.30
21-Ago	10:00	Cow+pig	60.00	90.00	16.00	
22-Ago	17:00	Cow	45.00	75.00	20.10	16.90
27-Ago	10:00	Cow	60.00	90.00	21.50	19.10
28-Ago	13:00	Cow	30.00	60.00	22.50	19.20

Appendix 2. Temperature readings and model results. Expressed in °C.

Day	Time	Greenhouse temperature (Tgh)	Cover temperature (Tco)	Reactor temperature (Tdg)	Temperature between digester and insulation (Ti)	Model cover temperature	Model reactor temperature
16-Ago	12:50	19.1	19	17.5	17.2	18.98	18.00
19-Ago	10:40	19.1	18.5	18	17	19.04	17.76
	13:20	17	16.3	18.7	17	17.27	17.14
	15:00	21.1	21.1	19.8	17	21.01	19.15
20-Ago	10:00	20	22.5	20	17	20.07	19.95
	17:00	21.8	21.3	19.2	16.2	21.55	18.88
21-Ago	10:00	22.3	21.6	19.2	16.9	21.99	19.39
	10:45	20	20.9	17.4	16.7	19.76	18.90
	12:10	21.5	21.1	18.4	16.7	21.19	19.01
	13:30	22	22.1	19.2	16.7	21.73	19.57
	15:00	22	22.3	19.8	16.7	21.80	19.69
22-Ago	17:00	25	23	20	17	24.45	20.24
23-Ago	10:45	22	22.5	18.6	17.3	21.66	20.09
	11:50	24	23	19.5	17.3	23.52	20.38
	12:50	25	23.9	20.1	17.4	24.46	20.97
	13:50	25.9	24.9	20.9	17.4	25.35	21.58
	15:00	27	25.8	21.5	17.4	26.38	22.15
26-Ago	10:30	23	23.1	20.7	19.4	22.79	21.42
	11:40	25.4	25.2	21.8	19.3	25.02	22.63
	12:50	28.5	27.5	22.6	19.3	27.82	23.97
	14:10	30	29	23.3	19.3	29.22	24.96
	15:00	30.4	29.2	23.6	19.3	29.60	25.10
27-Ago	10:00	24.8	24	20.6	19.1	24.35	21.75
	17:00	26	25	24.5	19.1	25.64	22.34
28-Ago	10:30	21	20.9	21	19.9	21.07	20.43
	11:50	24.3	23.2	21.4	20.2	24.01	21.85
	12:50	24.9	24.1	22	20.2	24.61	22.37
	13:50	24	24	22.2	20.1	23.84	22.27

Appendix 3. Biogas production model results

Day	Average reactor temperature (°C)	Average Y _v (L CH ₄ /daym ³)	Average biogas production rate (Lbg/daym ³)	Biogas production (L)
16/08/2019	17.50	100.17	166.11	548.17
19/08/2019	18.83	102.52	170.02	561.06
20/08/2019	19.60	103.69	171.96	567.47
21/08/2019	18.70	102.25	169.57	559.57
22/08/2019	20.00	104.22	172.83	570.35
23/08/2019	20.12	104.24	172.86	570.44
26/08/2019	22.40	106.48	177.46	585.63
27/08/2019	22.55	106.43	177.38	585.36
28/08/2019	21.65	105.91	176.52	582.51

RISK ASSESSMENT FORM

FIELD / LOCATION WORK

The Approved Code of Practice - Management of Fieldwork should be referred to when completing this form

<http://www.ucl.ac.uk/estates/safetynet/guidance/fieldwork/acop.pdf>

DEPARTMENT/SECTION: CIVIL, ENVIRONMENTAL AND GEOMATIC ENGINEERING

LOCATION(S): ROTHAMSTEAD RESEARCH (HARPENDEN) AND SURREY DOCKS FARM (LONDON)

PERSONS COVERED BY THE RISK ASSESSMENT: Alejandro Deville del Aguila

BRIEF DESCRIPTION OF FIELDWORK: Sample measurement, analysis and modelling the performance of a small-scale anaerobic digestion system using animal manure as feedstock. Field work consists of data collection of the inputs and outputs of the system as well as the overall thermal performance.

Consider, in turn, each hazard (white on black). If **NO** hazard exists tick **(NO✓)** and move to next hazard section.

If a hazard does exist tick **(YES✓)** and assess the risks that could arise from that hazard in the risk assessment box.

Where risks are identified that are not adequately controlled they must be brought to the attention of your Departmental Management who should put temporary control measures in place or stop the work. Detail such risks in the final section.

ENVIRONMENT

The environment always represents a safety hazard. Use space below to identify and assess any risks associated with this hazard

e.g. location, climate, terrain, neighbourhood, in

Examples of risk: adverse weather, illness, hypothermia, assault, getting lost. Is the risk high/medium/low?

outside organizations,
pollution, animals.

Adverse weather – Low risk

Illness – Low risk

Getting lost – Low risk

Assault – Low risk

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

<input type="checkbox"/>	work abroad incorporates Foreign Office advice
<input checked="" type="checkbox"/>	participants have been trained and given all necessary information
<input type="checkbox"/>	only accredited centres are used for rural field work
<input checked="" type="checkbox"/>	participants will wear appropriate clothing and footwear for the specified environment
<input checked="" type="checkbox"/>	trained leaders accompany the trip
<input checked="" type="checkbox"/>	refuge is available
<input checked="" type="checkbox"/>	work in outside organisations is subject to their having satisfactory H&S procedures in place
<input type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

EMERGENCIES

Where emergencies may arise use space below to identify and assess any risks

e.g. fire, accidents

Examples of risk: loss of property, loss of life

Loss of property – Medium risk

Onsite pathogen spread – Low risk

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

<input checked="" type="checkbox"/>	fire fighting equipment is carried on the trip and participants know how to use it
<input checked="" type="checkbox"/>	contact numbers for emergency services are known to all participants

<input checked="" type="checkbox"/>	participants have means of contacting emergency services
<input checked="" type="checkbox"/>	participants have been trained and given all necessary information
<input checked="" type="checkbox"/>	a plan for rescue has been formulated, all parties understand the procedure
<input type="checkbox"/>	the plan for rescue /emergency has a reciprocal element
<input type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:
<input type="checkbox"/>	UCL TRAVEL INSURANCE. https://travelcert.aig.com/#/activation (Passcode 850773)
<input type="checkbox"/>	OFF SITE WORK ITINERARY FORM TO BE COMPLETED BEFORE TRAVEL

Onsite-staff is trained to deal with emergencies.

FIELDWORK 1

May 2010

EQUIPMENT	Is equipment used?	NO		Move to next hazard
		YES	X	Use space below to identify and assess any risks

e.g. clothing, outboard motors.

Examples of risk: inappropriate, failure, insufficient training to use or repair, injury. Is the risk high / medium / low ?

Biogas explosion – Low risk

Methane inhalation – Low risk

Biol overflow – Medium risk

Insufficient training to manipulate the biodigester – Medium risk

Insufficient training to manipulate sensors – Medium risk

Gas release valve failure – Low risk

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

<input checked="" type="checkbox"/>	the departmental written Arrangement for equipment is followed
<input checked="" type="checkbox"/>	participants have been provided with any necessary equipment appropriate for the work
<input checked="" type="checkbox"/>	all equipment has been inspected, before issue, by a competent person
<input checked="" type="checkbox"/>	all users have been advised of correct use

special equipment is only issued to persons trained in its use by a competent person

OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

LONE WORKING	Is lone working a possibility?	NO	X	Move to next hazard
		YES		Use space below to identify and assess any risks

e.g. alone or isolated, lone interviews. Examples of risk: difficult to summon help. Is the risk high / medium / low?

CONTROL MEASURES Indicate which procedures are in place to control the identified risk

- the departmental written Arrangement for lone/out of hours working for field work is followed
- lone or isolated working is not allowed
- location, route and expected time of return of lone workers is logged daily before work commences
- all workers have the means of raising an alarm in the event of an emergency, e.g. phone, flare, whistle
- all workers are fully familiar with emergency procedures
- OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

FIELDWORK 2 May 2010

ILL HEALTH The possibility of ill health always represents a safety hazard. Use space below to identify and assess any risks associated with this Hazard.

e.g. accident, illness, personal attack, special personal Examples of risk: injury, asthma, allergies. Is the risk high / medium / low?

considerations or vulnerabilities.

Minor injury – Low risk

Major injury – Low risk

Allergies – Low risk

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- an appropriate number of trained first-aiders and first aid kits are present on the field trip
- all participants have had the necessary inoculations/ carry appropriate prophylactics
- participants have been advised of the physical demands of the trip and are deemed to be physically suited
- participants have been adequate advice on harmful plants, animals and substances they may encounter
- participants requiring medication have advised the leader of this and carry sufficient medication for their needs
- OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

TRANSPORT

Will transport be required

NO	<input type="checkbox"/>
YES	<input checked="" type="checkbox"/>

Move to next hazard

Use space below to identify and assess any risks

e.g. hired vehicles

Examples of risk: accidents arising from lack of maintenance, suitability or training

Is the risk high / medium / low?

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- Only public transport will be used

	The vehicle will be hired from a reputable supplier
	Transport must be properly maintained in compliance with relevant national regulations
	Drivers comply with UCL Policy on Drivers http://www.ucl.ac.uk/hr/docs/college_drivers.php
	Drivers have been trained and hold the appropriate licence
	There will be more than one driver to prevent driver/operator fatigue, and there will be adequate rest periods
	Sufficient spare parts carried to meet foreseeable emergencies
	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

DEALING WITH THE PUBLIC	Will people be dealing with public	NO	X	Move to next hazard
		YES		Use space below to identify and assess any risks
e.g. <i>interviews, observing</i>	Examples of risk: personal attack, causing offence, being misinterpreted. Is the risk high / medium / low?			

CONTROL MEASURES	Indicate which procedures are in place to control the identified risk			
	all participants are trained in interviewing techniques			
	interviews are contracted out to a third party			
	advice and support from local groups has been sought			
	participants do not wear clothes that might cause offence or attract unwanted attention			
	interviews are conducted at neutral locations or where neither party could be at risk			
	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:			

FIELDWORK 3

May 2010

WORKING ON OR	Will people work on	NO	X	Move to next hazard
----------------------	---------------------	----	---	---------------------

NEAR WATER

or near water?

YES

Use space below to identify and assess any risks

e.g. rivers, marshland, sea.

Examples of risk: drowning, malaria, hepatitis A, parasites. Is the risk high / medium / low?

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- lone working on or near water will not be allowed
- coastguard information is understood; all work takes place outside those times when tides could prove a threat
- all participants are competent swimmers
- participants always wear adequate protective equipment, e.g. buoyancy aids, wellingtons
- boat is operated by a competent person
- all boats are equipped with an alternative means of propulsion e.g. oars
- participants have received any appropriate inoculations
- OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

MANUAL HANDLING (MH)

Do MH activities take place?

NO

YES

X

Move to next hazard

Use space below to identify and assess any risks

e.g. lifting, carrying, moving large or heavy equipment, physical

Examples of risk: strain, cuts, broken bones. Is the risk high / medium / low?

unsuitability for the task.

Strains and contusions when moving heavy objects – Medium risk
Cuts – Medium risk

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

X	the departmental written Arrangement for MH is followed
	the supervisor has attended a MH risk assessment course
X	all tasks are within reasonable limits, persons physically unsuited to the MH task are prohibited from such activities
X	all persons performing MH tasks are adequately trained
X	equipment components will be assembled on site
X	any MH task outside the competence of staff will be done by contractors
	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

FIELDWORK 4

May 2010

SUBSTANCES

Will participants work with substances

NO	
YES	X

Move to next hazard

Use space below to identify and assess any risks

e.g. plants, chemical, biohazard, waste

Examples of risk: ill health - poisoning, infection, illness, burns, cuts. Is the risk high / medium / low?

Infection – Medium risk
Accidental ingestion of animal manure – Low risk
Accidental eye contact of animal manure – Low risk
Biohazard contact – Medium risk
Biohazard injection – Medium risk

Gas poisoning – Medium risk

CONTROL MEASURES	Indicate which procedures are in place to control the identified risk
<input checked="" type="checkbox"/>	the departmental written Arrangements for dealing with hazardous substances and waste are followed
<input checked="" type="checkbox"/>	all participants are given information, training and protective equipment for hazardous substances they may encounter
<input checked="" type="checkbox"/>	participants who have allergies have advised the leader of this and carry sufficient medication for their needs
<input checked="" type="checkbox"/>	waste is disposed of in a responsible manner
<input checked="" type="checkbox"/>	suitable containers are provided for hazardous waste
<input type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

OTHER HAZARDS	Have you identified any other hazards?	NO		Move to next section
		YES	X	Use space below to identify and assess any risks

i.e. any other hazards must be noted and assessed here.

Hazard: biohazard

Risk: is the risk high / medium / low?

Pathogen spread during sample transport – Medium risk

Pathogen contact/ingestion/injection during sample transport – Medium risk

CONTROL MEASURES	Give details of control measures in place to control the identified risks
-------------------------	--

All users transporting samples will be using the appropriate PPEs

Samples are only going to be transported in the appropriate containers at all times

Transport containers will be inspected by a competent person before sample transportation

The user transporting the sample will have at all times a first aid kit and disinfectants.

Have you identified any risks that are not adequately controlled?

NO	X
YES	

Move to Declaration

Use space below to identify the risk and what action was taken

Is this project subject to the UCL requirements on the ethics of Non-NHS Human Research?

YES		NO	X
-----	--	----	---

If yes, please state your Project ID Number

For more information, please refer to: <http://ethics.grad.ucl.ac.uk/>

DECLARATION

The work will be reassessed whenever there is a significant change and at least annually. Those participating in the work have read the assessment.

✓ Tick the appropriate statement:

I the undersigned have assessed the activity and associated risks and declare that there is no significant residual risk

I the undersigned have assessed the activity and associated risks and declare that the risk will be controlled by the method(s) listed above

NAME OF SUPERVISOR

Ilan Adler

SIGNATURE OF SUPERVISOR

DATE