AN INVESTIGATION INTO INCREASED PRODUCTIVITY OF SMALL SCALE ANAEROBIC DIGESTERS BY MEANS OF TEMPERATURE MANAGEMENT

By

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ABSTRACT

The use of biological waste as a primary energy source for the production of biogas, by the process of anaerobic digestion, has been commonly used in the past by small communities and on a larger scale by waste water treatment plants. In the latter, the biogas is traditionally used for heating of the digesters in order to increase process performance. Smaller scale anaerobic digesters using food waste as a primary energy source for biogas production could be implemented for residences and restaurants. The biogas produced could be used for cooking and heating purposes. Whilst common designs for such smaller digesters do not provide for heating, there may be warm waste water on site to elevate the operating temperature and thus improve gas yield.

This dissertation reports an experiment aimed at improving the performance of an existing anaerobic digester located at the Leo Marquard Hall (LMH) residence of the University of Cape Town. The 6 m^3 digester has been operated using food waste as its sole substrate. The volume of gas produced is unknown as there are no gas measurement devices on site. In the past it has been roughly estimated from pressure readings before and after gas use. The digester operates at ambient temperature which averages 16 °C over the year, which is suboptimal. The anaerobic digester is not equipped with a temperature measurement device to monitor operating temperature.

Two hypotheses were formulated and tested. The first stated that the temperature profile of the waste water leaving the LMH residence will have peaks in the morning and evening periods when the majority of students shower. The peak temperature periods will be in the morning before breakfast and in the evening after dinner. The temperature during these times is expected to be above 30 °C.

In order to test the first hypothesis, a thermocouple with temperature data logger was installed to record the temperature of waste water in the manhole drain leaving the LMH residence. The temperature data recordings confirmed the temperature peak of waste water leaving LMH residence at an average temperature of 30.5 °C in the morning. However, a clear evening temperature peak was not identified. Thus the hypothesis was only true for the morning temperature peak of waste water leaving LMH residence for weekdays when lectures take place.

The second hypothesis stated that, adding a portion of the 30 °C waste water into the LMH anaerobic digester will result in the digester running at 5 °C above the normal average operating temperature, and thus increase the productivity of the anaerobic digester.

In order to test the second hypothesis the design and installation of a pumped pipe system was completed in order to pump waste water from the LMH residence waste water outlet manhole gravity sewer to the LMH anaerobic digester. By loading the LMH anaerobic digester with 600 ℓ of warm waste water, the maximum digester temperature increase obtained was 5 °C relative to the normal cold water operation. The maximum increases in total weekly biogas and methane production achieved were 238 % and 260 % respectively, relative to the average weekly cold water operation.

The operating temperature of small scale anaerobic digesters is a very important factor for the performance of the anaerobic digester. This research shows that increasing the operating temperature of a small scale anaerobic digester by as little as 5 °C could double the performance of the anaerobic digester.

The site location for the installation of small scale anaerobic digesters should be investigated at design stage by taking into consideration the operating temperature. The digester could be installed in close proximity to both an organic waste stream and warm waste water stream that could affect the feasibility of a particular project installation.

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1 Introduction

Food waste which includes uneaten food and preparation leftovers is a form of domestic waste that is often not well managed. Quantities are significant: one recent study estimated it to make up 31.4% of the total food production in South Africa (CSIR: 2013). In the context of rising costs of energy and waste disposal, the latter driven by increasing concern with environmental quality degradation, conversion of food waste to energy is a more economically viable solution (Zhang *et al.,* 2007; Nikolausz *et al.,* 2013). Food waste to energy conversion processes includes anaerobic digestion, combustion and gasification. Of these, anaerobic digestion can be implemented at a range of scales, starting from household level, whilst combustion and gasification installations, treating mixed municipal waste, are only done at city level and great capital expenditure.

Anaerobic digestion is the biological process in which organic matter is broken down by microorganisms to produce biogas. The process takes place in an oxygen depleted environment, in which a series of bio-chemical reactions take place and the organic material is decomposed through the metabolic pathways of naturally occurring microorganisms.

1.1 Background

Generation of biogas from organic waste is a well-known technology, now considered mature after having attracted significant research interests after the 1970 oil crisis. China began a programme for the mass rollout of household anaerobic digesters in the year 1975, and within a few years units were being constructed at a rate of 1.6 million per year (Ho, 2005). However the units were of low quality design and by the 1980s most of these units were no longer operational. The pattern of mass rollout and failure of biogas digesters was repeated in India, Nepal, Vietnam and Sir Lanka. The technology and research has since improved and the units have become more robust with the use of polyethylene for the construction of digesters (Ho, 2005).

In South Africa the generation of biogas from the process of treating municipal waste water was seen as a by-product and for a long time, the gas was vented off to the atmosphere. However research has shown that biogas consists of 50% to 80% methane, which is 34 times more harmful than CO_2 as a greenhouse gas (IPCC: 2013). This has led to biogas being flared off to the atmosphere in South Africa as opposed to venting. Recently biogas on waste water treatment plans has been used for the heating of digesters either by heating water and passing in though a heat exchanger with sludge, or with the injection of steam. The latest use for the biogas has been the generation of electrical energy by using the biogas to fuel gas engines, which power electrical generators (energycity: 2015).

Researchers at the University of Cape Town commissioned a demonstration 6 m^3 prefabricated anaerobic digester (Biogas Pro, 2017) at the LMH residence in early 2011 (Naik et al., 2012). The LMH residence houses 419 male students. All students housed in the residence receive 2-3 meals a day which is prepared by the LMH kitchen. The digester is loaded with the food waste available from the kitchen and produces biogas which is used in the LMH residence kitchen for cooking. The digester is currently linked to a separate biogas stove, while the remaining cooking stoves use liquefied petroleum gas (LPG) for cooking. The LMH digester has recently been neglected and does not operate optimally at the moment. According to the digester manufacturer, the LMH digester has the potential to produce up to 1.9 m^3 of biogas per day when operated optimally at higher temperatures (Biogas Pro, 2017).

The operating temperature and temperature stability of the anaerobic digestion process affects the productivity of process. The higher the temperature, the higher the productivity of the process which decreases the retention time required for the substrate in the digester. Anaerobic digestion efficiency increases with increased temperature up to 37 °C in the mesophilic range and up to 60 °C for thermophilic cultures (Metcalf and Eddy, 2004).

1.2 Problem statement

Food and other biodegradable wastes can be used to produce biogas at a range of scales, but millions of small-scale digesters may not be producing biogas optimally, because of operating in a sub-optimal temperature range. Experiences with larger-scale anaerobic digesters, e.g. in waste-water treatment, show that the significant quantities of biogas produced, can be used as an energy source for the heating of digesters and generation of electricity by gas engine powered generators.

The demonstration biogas digester at UCT's LMH provides an opportunity to test whether biogas production can be augmented by using possibly available warm waste water. It is installed below ground level and thus is always operating at ground temperature which is not ideal. However, significant volumes of warm water should be generated in the residence in the evening and in the morning, passing the digester in a proximate sewer line. It is, however, not known how warm that water is when it passes by, and thus by how much it could speed up gas production in the digester if a certain quantity were fed in once or twice per day.

1.3 Objectives

This dissertation aims to investigate the performance of a 6 m^3 anaerobic digester organically loaded with food waste. The digester shall be hydraulically loaded with cold tap water during the control operation and warm waste water during the modified operation.

The first objective of this dissertation is to determine the temperature profile of the waste water leaving the LMH residence during week days and weekend days, in order to determine the periods of days when the peak temperature of waste water leaves the LMH residence. The consistency of the temperature peaks in waste water shall be analysed, to determine if it is feasible to load the digester with warm waste water.

The second objective of this dissertation is to determine the increase in performance of the LMH residence anaerobic digester at operating temperatures higher than the normal operation. The normal control operation of the LMH anaerobic digester is when the digester is hydraulically loaded with cold tap water. The digester operating temperature, biogas yield and methane yield shall be monitored to determine the control operating performance. The digester shall then be operated by hydraulically loading the digester with warm waste water. The increase in operating temperature, biogas yield and methane yield during the modified operation shall be compared to that of the control operation. The effect of temperature on the performance of the anaerobic digester shall be analysed and discussed.

2 Literature review

2.1 Overview

In this chapter, the theoretical basis for this dissertation is discussed. The chapter starts with a description of the anaerobic digestion process and the factors affecting the anaerobic digestion process. The practical and theoretical literature of biogas yield using food waste is described with a specific focus on biogas production at different temperatures. The LMH residence anaerobic digester is then described, since it is used as the basis of the experimental portion of this thesis. Literature on typical hot water shower temperature and volumes is discussed and interpreted relative to key features at LMH residence. The annual ambient temperature for the city of Cape Town is also reviewed as this is the normal operating temperature of the LMH anaerobic digester.

2.2 Small scale anaerobic digestion

Many rural African communities do not have access to electricity due to the low population densities and the large distances between communities which make centralised electricity generation with transmission relatively expensive (Amigun and von Blottnitz, 2010). Biogas production by the process of anaerobic digestion using organic waste provides an alternative energy source for heating, cooking and lighting (the latter less frequently since the advent of portable LED-battery-PV technology). Biogas plant also has the benefits of reducing environmental pollution, generating energy and production of a relatively safe source of plant nutrients for fertilising crops (Amigun and von Blottnitz, 2010). Small scale anaerobic digesters with a capacity less than 20 m^3 can provide an effective and alternative energy source to traditional fuels.

The traditional use of wood, straws, charcoal, dung and paraffin for cooking, heating and lighting can be replaced by biogas in rural communities, with some capacity and feedstock limitations. Burning of these traditional fuels generate gases and particulates, which result in lung and other respiratory diseases. Biogas as an alternative burns cleaner than these traditional fuels (Ottmar et al., 2012). These small scale digesters in the rural setting usually operate at ambient temperatures which is suboptimal.

2.3 The process of anaerobic digestion

The process of anaerobic digestion involves the breakdown of organic matter, which takes place in the absence of oxygen, and produces biogas as a by-product. The anaerobic digestion process requires different types of micro-organisms in order to breakdown organic matter in a multistep process. The process of anaerobic digestion takes place in four chemical or biochemical reactions namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. This science is widely discussed in biogas literature (e.g. Metcalf and Eddy, 2004), and is restated in sections 2.3.1 to 2.3.4 only to the extent it is influenced by temperature, specifically, lower than ambient temperature. The major micro-organisms which act symbiotically in anaerobic digestion are introduced in sections 2.3.5 and 2.3.6.

2.3.1 Hydrolysis

The first reaction is hydrolysis which is the decomposition of particulate organic material to form soluble compounds that can then be hydrolysed further to form simple monomers that are used by bacteria that perform fermentation (Metcalf and Eddy, 2004). The reaction is catalysed by enzymes such as cellulase, protease and lipase extracted from the hydrolytic and fermentative bacteria. The products of this reaction are soluble sugars, amino acids, glycerol and long chain carboxylic acids (Ralph and Dong, 2010). Hydrolysis is a slow energy consuming reaction relative to the rest of the reactions in the anaerobic digestion process, it is usually considered as the overall limiting step for the complete anaerobic digestion of complex polymers (Gallert and Winter, 1999)

2.3.2 Acidogenesis

The second reaction is fermentation or acidogenesis which is the formation of soluble organic compounds and short chain organic acids. In this process amino acids, sugars and fatty acids are degraded further. Organic substrates serve as both the electron donors and acceptors. The products of fermentation are acetate, hydrogen, carbon dioxide, propionate and butyrate. The propionate and butyrate are further fermented to produce hydrogen, carbon dioxide and acetate. The final products of fermentation which are acetate, hydrogen and carbon dioxide are needed for the methanogenesis reaction (Metcalf and Eddy, 2004). The free energy change associated with the conversion of propionate and butyrate to acetate and hydrogen requires that hydrogen be at low concentrations in the system or the reaction will not proceed (McCarty and Smith, 1986). Acidogens have notably higher growth rates compared to the methanogens and can survive extreme conditions such as low pH, high temperatures and high organic loading rates (Ahring et al., 2001)

2.3.3 Acetogenesis

In this reaction molecular weight volatile fatty acids are converted into acetate, hydrogen gas and carbon dioxide by acetogenic bacteria. The reaction can only be thermodynamically favoured if the partial pressure of hydrogen is kept low (Gerardi, 2003).

2.3.4 Methanogenesis

The fourth reaction is methanogenesis which is the bacterial conversion of organic acids into methanogens and carbon dioxide (Metcalf and Eddy, 2004). A group of organisms known as methonogens are responsible for the reaction. Two groups of methanogenic organisms are involved in methane production. One group, termed aceticlastic methanogens, split acetate into methane and carbon dioxide. The second group, termed hydrogen-utilizing methanogens, use hydrogen as the electron donor and carbon dioxide as the electron acceptor to produce methane. Bacteria within the anaerobic process called acetogens are also able to use carbon dioxide to oxidize hydrogen and form acetic acid. However, the acetic acid will be converted to methane, so the impact of this reaction is minor. The majority of the methane produced in anaerobic digestion is from acetate formation (Metcalf and Eddy, 2004).

2.3.5 Acetate forming bacteria

Acetate forming bacteria grow in conjunction with methane forming archea. Acetate serves as a substrate for methane forming archea. Hydrogen is produced when acetate forming bacteria produce acetate. The hydrogen accumulates and significant hydrogen pressure occurs, the pressure results in termination of acetate forming bacteria and a loss of acetate production. The methane forming bacteria uses the hydrogen in the production of methane. Acetate forming bacteria are hydrogen producers and survive only at very low concentrations of hydrogen in the environment. They can only survive if their metabolic waste, hydrogen, is continuously removed. This is achieved because of their symbiotic relationship with hydrogen utilizing bacteria or methane forming bacteria (Prabhudessai, 2013).

2.3.6 Methane forming Archaea

Methanogens are grouped in the domain Archaea. Hydrogen consuming methane production results in the greater energy gains for methanogens than acetate degradation (Von Stockar et al., 2006). Hydrogen and carbon dioxide are converted into methane therefore entropy decreases and heat is liberated in this reaction. However, acetate oxidation is entropy driven reaction in anaerobic cultures, thus entropy is increased as the reaction is completed. The entropy is increased by turning one molecule in an aqueous state into two gaseous molecules, methane and carbon dioxide, which increases entropy considerably (Vlyssides et al., 2008). Although methane production using hydrogen is the more effective process of energy capture by methanogenesis, less than 30% of the methane produced in the anaerobic digester occurs by this method due to the limited hydrogen in an anaerobic digester (Gerardi, 2013).

2.4 Factors affecting small scale anaerobic digestion

There are many factors that affect the productivity of the anaerobic digestion process which include microbial population, acidity, carbon to nitrogen mass ratio, temperature, particle size of substrate, organic loading rate, hydraulic retention time, mass fraction of solids, reactor configuration, oxidation-reduction potential and inhibition-toxicity. This section will introduce all of the factors in as much as they are of relevance to the type of digester operated at LMH and focus on the factors that are likely to be most influenced by changes that would result in a small-scale anaerobic digester when switched from operating mainly on food waste to being fed regularly with warm waste water, in addition to receiving food waste.

2.4.1 Microbial population

Biogas production relies on many different types of micro-organisms, each with their own optimum conditions and with substrates and products affecting the physio-chemical environment. Each reaction of the process is carried out by a different subset of micro-organisms operating in their own unique conditions (Cheng et al., 1987). At the start-up of an anaerobic digester, inoculation is usually needed: this is the introduction of the microbial culture into the digester, usually from cow manure or from other waste water treatment plants (Cheng at al., 1987).

2.4.2 pH

The pH of the digester is an important performance and stability indicator. The pH level changes in response to biological conversions during the different processes of anaerobic digestion. A stable pH indicates that the system is in equilibrium and the digester operation is stable. The processes of acidification and methanogenesis which take place during digestion require different pH levels for optimal process control. The acidogenic bacteria prefer a pH range between 5.5 and 6.5 while the methanogenic bacteria prefer a range of 7.8 to 8.2 (Boe K, 2009), and larger process plant is therefore sometimes designed with two separate reactors, each operating at its optimal pH. In the environment where both cultures exist which is the case in small scale anaerobic digesters, the optimal pH range is 6.8 to 7.2 (Gerardi, 2003).This accords well with the report by Zhang et al. (2007) that anaerobic digestion of kitchen wastes at a controlled pH value of 7 resulted in a relatively high rate of hydrolysis and acetogenesis, with about 86% of the total organic carbon and 82% of the chemical oxygen demand being solubilised.

The pH affects the functionality of the micro-organisms (Brummeller, 1989). The products from the hydrolysis reaction, which are organic acids, lower the pH in the digester (Kleinstreuer, 1982). If the pH gets too low, the methanogens cannot convert the acids into methane, and the system fails. However as methane forming bacteria consume the volatile acids, alkalinity is produced, and the pH of the digester increases and then stabilises. The organic acids produced are therefore seen as inhibitory substances. Thus the pH of the digester should always be monitored to make sure it does not decrease to the point of the system failing.

The pH can be controlled by monitoring the feed substrate and making sure that it is either alkaline enough, or not too easily hydrolysed so as to cause a pH drop. In a properly operating anaerobic digester a pH between 6.8 and 7.2 occurs as volatile acids are converted to methane and carbon dioxide. The pH of an anaerobic digester is significantly affected by the carbon dioxide content of the biogas (Prabhudessai, 2013).

Digester stability is enhanced by a high alkalinity concentration. The composition and concentration of the feed substrate directly influence the alkalinity of the digester. Feed substrates with large quantities of proteinaceous wastes transferred to the digester are associated with relatively high concentrations of alkalinity. The alkalinity is the result of the release of amino groups (NH_2) and production of ammonia as the proteinaceous wastes are degraded. However, normally alkalinity is present primarily in the form of bicarbonates that are in equilibrium with carbon dioxide in the biogas at a given pH (Prabhudessai, 2013).

If the feed substrate to the anaerobic digester does not contain alkali compounds, alkalinity must be added to the digester to maintain stable and acceptable values for alkalinity and pH. If the acid production exceeds the rate of methane production, alkalinity must be added in the form of bicarbonates (Prabhudessai, 2013).

2.4.3 Substrate characteristics

The characterization of the substrate entering the digester is an important factor for the design and optimization of the waste treatment and disposal. These properties affect biogas production and process stability during the anaerobic digestion process. Examples of these properties are moisture content, volatile solids content, nutrients, particle size, and biodegradability. Data on wastes and the amount of organic matter in terms of volatile solids and biochemical methane potential is known and presented in literature and many textbooks. However the anaerobic biodegradability of organic matter depends on its composition, and the amount of methane produced depends on the biochemical nature of the waste (Buffiere et al., 2006).

Carbohydrates, proteins and fats show different methane production rates (Angelidaki and Sanders, 2004). Fats have the highest methane yield per unit mass when compared to most organic materials. Although organic waste with a high fat content is an attractive substrate for biogas production, the hydrolysis of fats takes longer than proteins and hydrocarbons and thus it requires a longer retention time within the digester (Neves et al., 2008). The reason for the decreased rate of hydrolysis is due to a synergistic effect on the degradation of other components since fats attach onto solid surfaces and may delay the hydrolysis process by reducing the accessibility of bacteria to the fats.

The composition of waste also determines the relative amounts of organic carbon and nitrogen present in the waste substrate. This is known as the carbon to nitrogen ration (C/N ratio). The higher the C/N ratio of the feed substrate the less suitable it will be for bacterial growth due to a deficiency of nitrogen, however the hydrolysis reaction will be fast due to the high carbon content. As a result the gas production rate and solid degradability will be low while the high rate of hydrolysis will decrease the pH in the digester. This decrease in pH could cause the methanogenic bacteria to die off and will cause the digester to fail.

The lower the C/Nratio of the feed substrate the more ammonia present in the digester due to excess nitrogen in the digester. Ammonia accumulation is toxic to the bacteria within the digester (Angelidaki and Sanders, 2004). The optimum ratio of carbon to nitrogen for stable operation of an anaerobic digester is in the range of 30:1 to 20:1(Bermal:2009).

2.4.4 Temperature

The operating temperature of the anaerobic digester has a substantial effect on the rate of digestion. The reaction rates of hydrolysis and methanogenesis are strongly affected by the operating temperature of an anaerobic digester. The optimum temperatures for bacterial activity are in the range from 25°C to 35°C. When the temperature drops to about 15°C, methane producing bacteria become quite inactive and at about 5°C, the autotrophic nitrifying bacteria practically cease functioning (Metcalf and Eddy, 2004).With increasing temperature the reaction rate of anaerobic digestion strongly increases, thus promoting application at higher organic loading rates without affecting the organic removal efficiency (Desai et al., 1994). The relationship between the rate of digestion and the temperature is non-linear and would decrease at temperatures above 70 °C because the microbial bacteria would start to die (Metcalf and Eddy, 2004).

The operating temperature of the digester also effects the retention time required within the digester. The Biogas Handbook (2008) states that anaerobic digesters operating at temperatures below 20°C operate in the psychrophilic temperature range and require a minimum hydraulic retention time of 70 to 80 days. By contrast, digesters operating in temperature regions between 30°C and 42°C operate in the mesophilic temperature range and only require a minimum hydraulic retention time of 30 to 40 days.

Most large scale digesters are designed to operate within the mesophilic temperature range of 30°C to 35°C, whilst some digesters are designed to operate at higher temperatures of 50 °C to 60°C which is known as the thermophilic temperature range (Metcalf and Eddy, 2004). The constant temperature ranges above ambient temperature are obtained by heating and insulating the digesters to decrease heat loss. Small-scale digesters often are not heated and usually poorly insulated, and therefore operate at ambient, or close to ambient conditions. Small scale digesters are also installed below ground level which decreases the effect of ambient temperature on the digester operating temperature.

In the thermophilic temperature range fluctuations as low as 2°C can result in 30% less biogas production (Zupancic and Jemec, 2010) therefore temperature fluctuations of more than 1°C cannot be tolerated, however in the mesophilic temperature range the microorganisms are less sensitive and fluctuations of 3 °C can be tolerated. Larger temperature variations are tolerable as the operating temperature of the anaerobic digester decreases (Zupancic and Jemec, 2010).

2.4.5 Particle size and mixing

The particle size of the feed substrate plays an important role in the anaerobic digestion process, especially during the hydrolysis reaction. The smaller the particle size the higher the rate of anaerobic digestion due to the larger surface area of organic matter in contact with the microbial bacteria/enzymes (Hartmann and Ahring, 2006). The smaller particle size can be achieved by mechanical maceration of the feedstock.

Mixing increases contact between the microbial bacteria and the organic matter preventing the accumulation of substrates and intermediates and guarantees homogenous conditions in the digester (Angelidaki et al., 2009). Mixing within the digester also prevents thermal stratification and the formation of a surface crust/scum build up in an anaerobic digester (Karim et al.,2005). Furthermore, mixing ensures that solids remain in suspension avoiding the formation of dead zones by sedimentation of dense solid particles. Mixing also enables the particle size reduction as digestion progresses and the release of produced biogas from the digester contents (Kaparaju et al, 2007).

2.4.6 Hydraulic retention time and organic loading rate

Hydraulic retention time refers to the time that a certain volume of liquid fed with the substrate resides in a digester. The hydraulic retention time is determined by the average time needed for decomposition of the organic material, as measured by the chemical oxygen demand of the influent and the effluent material. The longer the substrate is kept under proper reaction conditions, the more complete the degradation of the substrate. The rate of the reaction decreases with longer residence time, indicating that there is an optimal retention time that will achieve the benefits of digestion in a cost effective way (Vishwanath et al., 1994). A low hydraulic retention time (which is the same as a high hydraulic loading rate) could lead to a washout of the microbial population from the digester faster than they can reproduce, which leads to failure of the process.

The organic loading rate is defined as the amount of organic matter expressed in terms of volatile solids or chemical oxygen demand that must be treated by a certain volume of anaerobic digester in a certain period of time. The organic loading rate is another important factor affecting the production of biogas and stability of anaerobic digestion. If the organic loading rate is too high, the process becomes unstable due to an increase in the production of volatile fatty acids above the desired amount (Kiely, 2009). The increased production of carbon dioxide associated with high organic loading rates (resulting from excessive hydrolysis) causes foaming in the digester which leads to operational problems. On the other hand, a lower organic loading rate lowers the production of biogas. Thus, finding the optimum organic loading rate is essential for optimum performance of the digester.

2.4.7 Total solids content

Anaerobic digestion processes can be termed as either “wet” or “dry” digestion depending on the total solids concentration of the feed substrate. The anaerobic digestion process is defined as wet if the total solids concentration of the feed substrate is less than 15% and in dry digestion the total solids concentration may reach 20-40% (Lissens et al.,2001).

In a wet digestion process, the solid waste has to be conditioned to the appropriate solids concentration by adding process water either by recirculation of liquid effluent fraction or by co-digestion with liquid waste. The application of a wet digestion process offers several advantages such as dilution of inhibitory substances by process water and requirement of less sophisticated mechanical equipment. However disadvantages such as complicated pre-treatment, high consumption of water, high energy consumption for heating and the reduction of working volume due to sedimentation of inert material have to be taken into account (Banks and Stentiford, 2007).

Dry anaerobic digesters offers less complicated pre-treatments and higher loading rates compared to wet anaerobic digesters. However the system require more sophisticated mechanical equipment (Lissens et al.,2001) and less possibility to dilute the inhibitory substances (Vandevivere et al., 2003). Complete mixing of the digestate is not possible in these reactors and as a result individual processes may run in different parts of the reactor, which limits an optimal co-operation of the microbial groups involved in the digestion (Hartman and Ahring, 2006).

Smaller scale domestic digesters are almost invariably the wet type.

2.4.8 Digester feeding types

There are two types of feeding systems for anaerobic digestion, the batch feeding system and the continuous feeding system.

In the batch feeding system, digesters are filled once with fresh substrate with or without addition of inoculation and sealed for the duration of the retention time, after which the digester is opened and the effluent is removed. These digesters have a simple design, process control, robustness toward coarse and heavy contaminates, and lower investment costs make them particularly attractive for developing countries (Mata-Alvarez, 2002). The batch type feeding digesters are used in the treatment of municipal solid waste and are usually dry type digesters.

The continuous feeding system is a constant supply of fresh feedstock to the digester and the same quantity of digested material is removed from the digester. The continuous feed system has the advantages of more complete mixing, better heating, and a higher rate of digestion when compared to the batch type system. The continuous type feeding digesters are usually wet type digesters, with the fresh digester feedstock entering the digester and displacing the digested material out of the digester (Mata-Alvarez, 2002).

Smaller digesters are often not continuously fed, but rather intermittently, such as once or twice per day.

2.4.9 Oxidation reduction potential

The bacteria responsible for producing methane are very sensitive to oxygen content and the presence of oxygen in the digester reduces the productivity of the digester. The anaerobic process has a certain tolerance to oxygen it can handle (Naik et al, 2014). The redox potential of the digester contents can be used as a measure of the methanogenic bacterial growth. The redox potential for growth requires a relatively low potential in the region of 200 to 400 mV (DB Archer; 1986).

2.4.10 Inhibition and toxicity

The bacteria responsible for anaerobic digestion can be inhibited by substances present in the influent waste. Ammonia, halogenated compounds, heavy metals and cyanide can kill the bacteria required for the anaerobic digestion process. Metabolic by products of microorganisms such as ammonia, volatile fatty acids and sulphide can also kill bacteria responsible for the anaerobic digestion process (Naik et al, 2014).

2.5 Theory of calculating biogas yield from anaerobic digestion of food waste and domestic sewage

The quantity and rate of biogas and methane produced from a specific anaerobic digestion system depends on the list of factors described in section 2.4. The following subsections review past studies to get a range of biogas production and biogas production rates from anaerobic digesters operating at different temperatures using food waste as the feed substrate.

2.5.1 Biogas and methane production from food waste

The quantity and rate of biogas production depends on many factors as detailed in section 2.4. The quantity of biogas produced from a specific quantity of substrate depends on the characteristics of the substrate specifically the fraction of volatile solids (VS). Biogas produced from a substrate is commonly expressed in volume of biogas yield per mass of volatile solids entering the digester. The methane content of the biogas, which is an indication of the calorific value of the biogas, is expressed as a percentage of total biogas produced. The following paragraphs summarise experimental results from various studies to quantify typical biogas yields from food waste at different operating temperatures:

A study conducted in San Francisco by the University of California showed the results of a batch type anaerobic digester using food waste as the feed substrate with a VS/TS ratio of 85.3 %. The digester methane production was 348 and 435 mℓ/g VS, respectively, after 10 and 28 days of digestion at 50°C, with 80 % of the methane produced in the first 10 days of digestion. Methane accounted for 73% of the biogas produced (Zang et al,. 2006).

A study done by Cho and Park (1995) obtained methane production values of 472 mℓ/g VS at 37 °C after 25 days. The food waste was pulverised before being added to the 2 stage digester. The feed substrate VS/TS ratio was 95%

Another study done by Heo et al,(2004) obtained methane production values of 489 mℓ/g VS added, by anaerobic digestion at 35 °C after 40 days, with a VS/TS ratio of food waste tested at 95%.

Steffen et al. (1998) reported the biogas yield from anaerobic digestion of food waste to be 480 mℓ/g VS with no indication of digester conditions or methane content of biogas.

Thus the quantity of methane production from these studies ranges between 435 to 489 mℓ/g VS at temperatures above 30°C after 25 to 40 days digestion, these digesters described above are all loaded initially and allowed to digest for the duration of the retention time.

2.5.2 Biogas and methane production from municipal solid waste and domestic sewage

The study conducted by Elango et al. (2006) reported the biogas yield from anaerobic digestion of feed stock containing both Municipal Solid Waste (MSW) and domestic sewage. The 5 ℓ digesters where seeded with 2 ℓ of feed sludge and 2.75 ℓ of feed stock while operated on a semi-continuous mode with daily feeding of 0.18 ℓ of feed stock. The operating temperature and hydraulic retention time of the digesters was maintained at 26 to 36 °C and 25 days respectively, throughout the experiment.

The biogas production increased from 130 to 360 mℓ/g VS added, as the organic feeding rates increased from 0.5 to 2.9 kg of VS/m^3/day. Further increase in of organic loading resulted in decreased biogas production rates. The average methane content of the biogas produced was 70%.

2.5.3 Biogas and methane production rates

The rate of methane production can be expressed as the volume of methane produced in litres per day, per litre of reactor volume (ℓ/ℓ.d). The rate of biogas production from anaerobic digestion also depends on the factors listed in section 2.4. This chapter covers studies of anaerobic digestion of food waste/MSW and the rate of biogas production. Studies below consider both batch and continuous type operation.

The study described above by Zang et al. (2006) produced methane at an average rate of 0.21 ℓ/ℓ.d when operated at 50°C during a 28 day period in a batch type operated digester. However, with 80% of the methane produced in the first 10 days, the production rate during that initial period was about 0.4 ℓ/ℓ.d.

The results of a study done by Kim et al (2006), using food waste for anaerobic digestion in a three stage digester is described below. The biogas and methane production at different temperatures are shown in the Table 2-1.

Table 2-1: Rate of biogas production from food waste (Kim et al, 2006)

Anaerobic digestion of food waste with HRT of 10 days			
Temperature (°C)	Biogas production (ℓ/d)	Biogas production per reactor volume (ℓ/ℓd)	Methane production per reactor volume (ℓ/ℓd)
40	7.3	0.91	0.56
45	8.7	1.09	0.69
50	10.4	1.30	0.84
55	6.8	0.85	0.46

The results show that with increasing operating temperature the biogas and methane production increases up to 50°C after which point there is a decrease in biogas and methane production. The experimental work was done using an 8 ℓ working volume and the digester was initially loaded and allowed to digest for the total retention time of 10 days.

A study done by He et al. (2006) at the Beijing University of Chemical Technology investigated the effect of temperature on hydrolysis and acidification of food waste. The food waste was shredded into a slurry state and added to a 2 ℓ working volume anaerobic digester. The feeding load was 15 g/ℓ VS and the experiments were done at temperatures 35 °C, 55 °C and 70 °C. These temperatures were chosen to correspond with mesophilic, thermophilic and hyperthermophilic temperature ranges. The results of the biogas production are shown in the Figure 2-1.

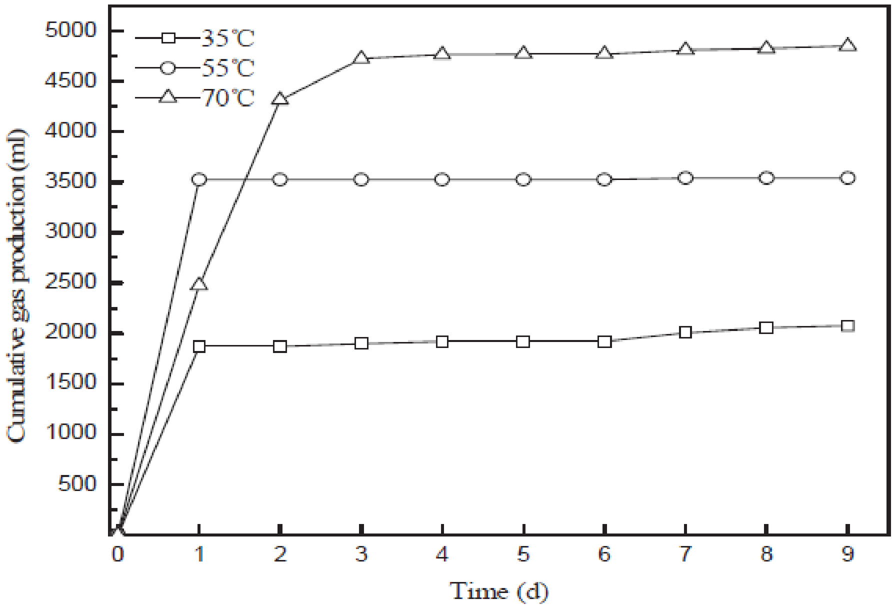


Figure 2-1: Biogas production (He et al, 2006)

The biogas production at 35 °C, 55 °C and 70 °C was 2.1 ℓ, 3.5 ℓ and 4.8 ℓ respectively. These results also show that with increasing operating temperature the rate of biogas production increases.

The following study by Banks et al. (2010) analyses the results of a full scale 900 m³ anaerobic digester operating at 42°C in order to produce biogas for electrical power generation. The digester was operated continuously for 462 days using macerated food waste as the feed substrate. The digester was also continuously mixed. The average solids content of the food waste was 27.7% TS and 24.4% VS. The biogas produced from the digester is shown in Table 2-2 below.

Table 2-2: Biogas produced from food waste (Banks et al, 2010)

	Total gas produced (m³)	Total gas produced daily (m³/d)	Gas produced per digester volume (ℓ/ℓ.d)
Biogas	615472	1332.19	1.48
Methane	385488	834.39	0.93

The biogas and methane produced per digester volume in this study is higher than the study done by Kim et al (2006) at 40°C or 45°C. This could be due to the increased mixing, maceration and substrate difference between the two systems.

The study conducted by Elango et al. (2006) discussed in section 2.5.2, produced biogas at a rate of 0.00234 to 0.0376 ℓ/ℓ.d, using MSW and domestic sewage as the feed stock. The average operating temperature of this study was 26 to 36 °C. The digesters produced biogas at an average methane content of 70%, thus the volume of methane produced in litres per day, per litre of reactor volume was 0.0016 to 0.0263 ℓ/ℓ.d. These figures are much lower than that of the Banks et al. (2010) analyses.

The studies discussed show different rates of biogas and methane production per digester volume at similar temperatures using food waste as the feed substrate. The literature indicates that each system is unique depending on all the operational factors listed in chapter 2.4. The literature demonstrates that for digesters operated with semi-continuous feeding of food waste/MSW, produced biogas and methane between 0.0016 to 0.93 ℓ/ℓ.d. The literature does however show that for a specific system, the rate of biogas and methane production increases with an increase in operating temperature of the anaerobic digester.

2.5.4 Modelling the effect of temperature on biogas production

The kinetics of a process is related to the temperature of the process through the Arrhenius relationship (Metcalf & Eddy, 2004). For a given catalytic or microbial system, with given chemical components, this relationship is shown in the Arrhenius function below:

$$ln\frac{k_1}{k_2} = \frac{E(T_2-T_1)}{RT_1T_2} = \frac{E}{RT_1T_2} \qquad (1)$$

Where k_1 = reaction rate constant at temperature T_1 (ℓ/s, ℓ/min, etc.)

k_2 = reaction rate constant at temperature T_2 (ℓ/s, ℓ/min, etc.)

T = temperature in Kelvin

E = constant characteristic of the (e.g. activation energy), J/mol

R = ideal gas constant, 8.314 J/mol.k

The Arrhenius function can be modified and simplified, to derive the Modified Arrhenius Function, which can be used to describe the kinetics of the degradation process occurring within many reacting biological systems including anaerobic digestion (Sheridan et al., 2012). The derivation of the Modified Arrhenius Function (MAF) is based on the assumption that the operating temperature is close to or below 20°C (Sheridan et al, 2012).

$$k = k_{20}.\theta^{(T-20)} \qquad (2)$$

Where: θ = temperature correction factor

T = temperature in degrees Celsius

k_{20} = reaction rate at 20 degrees Celsius

The MAF is attractive as an experimental equation because of its ease of use, the temperature is given in degrees Celsius and the temperature correction factor is measureable. The graph below shows how the reaction rate increases with temperature for both the Arrhenius equation and the Modified Arrhenius equation (Sheridan et al., 2012).

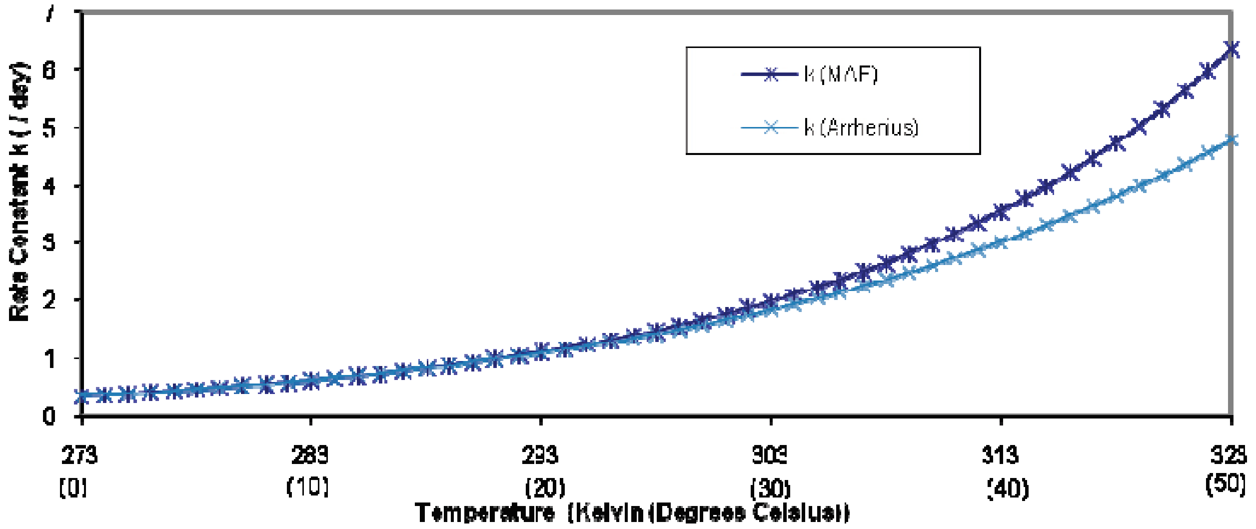


Figure 2-2: comparisons of the rate constants as calculated by the MAF and the Arrhenius equation showing differences at higher temperatures (Sheridan et al., 2012)

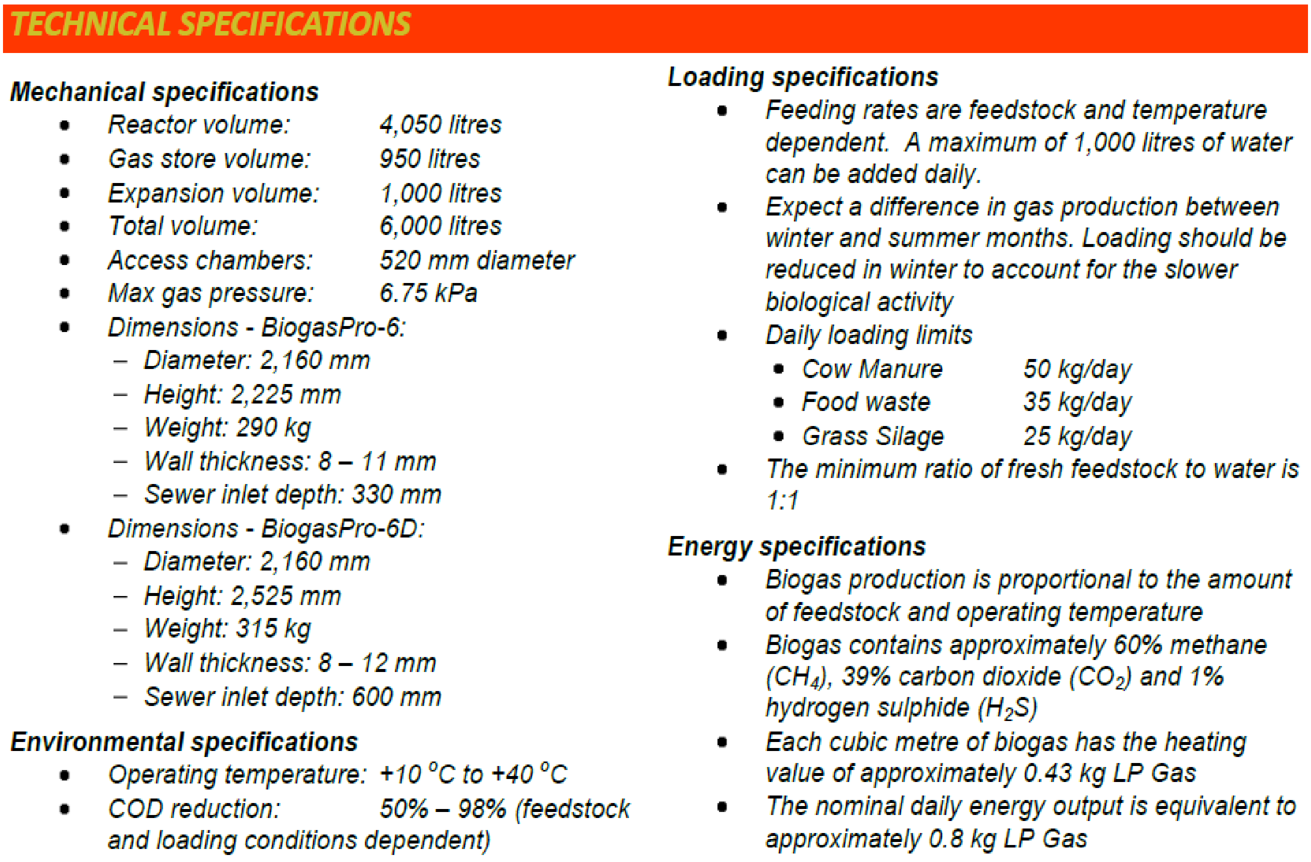
The Figure 2-2 shows that by increasing the operating temperature from 10 °C to 20°C the reaction rate doubles. Theoretically a specific anaerobic digesters performance could be increased by 100 % with a 10 °C increase in temperature.

2.6 Leo Marquard Hall (LMH) residence anaerobic digester

The LMH residence has a 6 m^3 Agama Biogas Pro, fixed dome digester installed on the residence property. The digester is installed below ground level and is not thermally insulated. The digester is constructed from linear low density polyethylene, with a reactor volume of 4 m^3, a gas storage volume of 1 m^3, and an expansion volume of 1 m^3 (Biogas Pro, 2017). The gas leaving the digester is piped to a separate biogas hob inside the LMH residence kitchen, where the biogas is used for cooking. A mechanical pressure gauge is installed in parallel between the biogas hob and the digester to measure the static pressure between the hob and digester.

The feed substrate used is food waste from the LMH residence kitchen mixed with cold tap water. Agama specifies the maximum hydraulic loading rate of the LMH digester to be 1 m^3 per day. The mechanical and technical specifications of the digester are shown in Table 2-3 (BiogasPro Agama: 2017).

Table 2-3: Agama BiogasPro technical specifications



TECHNICAL SPECIFICATIONS

Mechanical specifications

- *Reactor volume: 4,050 litres*
- *Gas store volume: 950 litres*
- *Expansion volume: 1,000 litres*
- *Total volume: 6,000 litres*
- *Access chambers: 520 mm diameter*
- *Max gas pressure: 6.75 kPa*
- *Dimensions - BiogasPro-6:*
  - *Diameter: 2,160 mm*
  - *Height: 2,225 mm*
  - *Weight: 290 kg*
  - *Wall thickness: 8 – 11 mm*
  - *Sewer inlet depth: 330 mm*
- *Dimensions - BiogasPro-6D:*
  - *Diameter: 2,160 mm*
  - *Height: 2,525 mm*
  - *Weight: 315 kg*
  - *Wall thickness: 8 – 12 mm*
  - *Sewer inlet depth: 600 mm*

Environmental specifications

- *Operating temperature: +10 °C to +40 °C*
- *COD reduction: 50% – 98% (feedstock and loading conditions dependent)*

Loading specifications

- *Feeding rates are feedstock and temperature dependent. A maximum of 1,000 litres of water can be added daily.*
- *Expect a difference in gas production between winter and summer months. Loading should be reduced in winter to account for the slower biological activity*
- *Daily loading limits*
  - *Cow Manure 50 kg/day*
  - *Food waste 35 kg/day*
  - *Grass Silage 25 kg/day*
- *The minimum ratio of fresh feedstock to water is 1:1*

Energy specifications

- *Biogas production is proportional to the amount of feedstock and operating temperature*
- *Biogas contains approximately 60% methane (CH_4), 39% carbon dioxide (CO_2) and 1% hydrogen sulphide (H_2S)*
- *Each cubic metre of biogas has the heating value of approximately 0.43 kg LP Gas*
- *The nominal daily energy output is equivalent to approximately 0.8 kg LP Gas*

The LMH anaerobic digester was operated by the Environmental and Process Systems Engineering Research Group (E&PSE) from April 2011 to April 2012 (Naik et al., 2012). The digester was inoculated with cow manure before organic loading with kitchen waste. The pH, pressure, temperature, hydraulic loading, the amount and type of food waste fed to the digester was monitored daily. Once the operation of the anaerobic digester was stable, LMH digester was producing on average enough biogas to be burnt for 2.5 hrs per week over a 10 week period. The digester was fed on average 46 kg of food per week during the 10 week period (Naik et al., 2012). The operating temperature during the 10 week period varied between 14 °C and 20 °C.

2.7 Shower water temperature and quantities

Hot water heaters or geysers are used for the heating of water in residential homes and larger scale residences and hotels in the hospitality sector. Research done by Jacobs and Haarhoff from the University of Stellenbosch relies on different literature from South Africa and around the world in order to model the water end use in the residential sector. The average volume of hot water used per shower per person in various studies was about 60 ℓ (Jacobs and Haarhoff, 2004).

The typical thermostat setting of hot water geysers in South Africa varies between 60 °C and 70 °C with an average setting of 65°C (Jacobs and Haarhoff, 2004). When an individual showers, the hot water is not used at the thermostat setting, it is rather blended with cold water to a desirable hot water temperature. The typical blended hot water temperature used when showering is about 40 °C (Jacobs and Haarhoff, 2004). The hot water leaving the shower into the drainage system is thus expected to be less than 40 °C due to heat losses in the pipe work of the drainage system. The research also shows that on average 1 in 3 individuals shower everyday (Jacobs and Haarhoff, 2004).

Another study done in Hong Kong also showed that the average blended temperature in a shower head remained relatively constant throughout the summer and winter months at 40.9 °C (Wong et al,. 2009). The temperature during showering was also measured and it was determined to be 6°C to 2 °C lower than the shower head temperature (Wong et al. 2009). The temperature of the hot water leaving the shower in the drain would be 34 °C on average.

LMH residence houses 420 male students (UCT, 2016). If it is assumed that one third of all students shower once per day, the estimated volume of hot shower water leaving the residence is calculated to be 8.4 m^3/day at 34 °C.

2.8 Ambient temperature in Cape Town

The average ambient temperature for Cape Town is shown in Figure 2-3 below (World weather, 2016). The average annual temperature in Cape Town is 17°C (climate maps, 2016). The coldest months of the year in Cape Town are June, July and August with an average temperature of 13.3 °C while the warmest months of the year are December, January, February and March with an average temperature of 21.6 °C. The ambient temperature will affect the operating temperature of the LMH anaerobic digester. However the digester is installed below ground level covered with soil which has both an insulating and stabilising effect on the operating temperature of the digester.

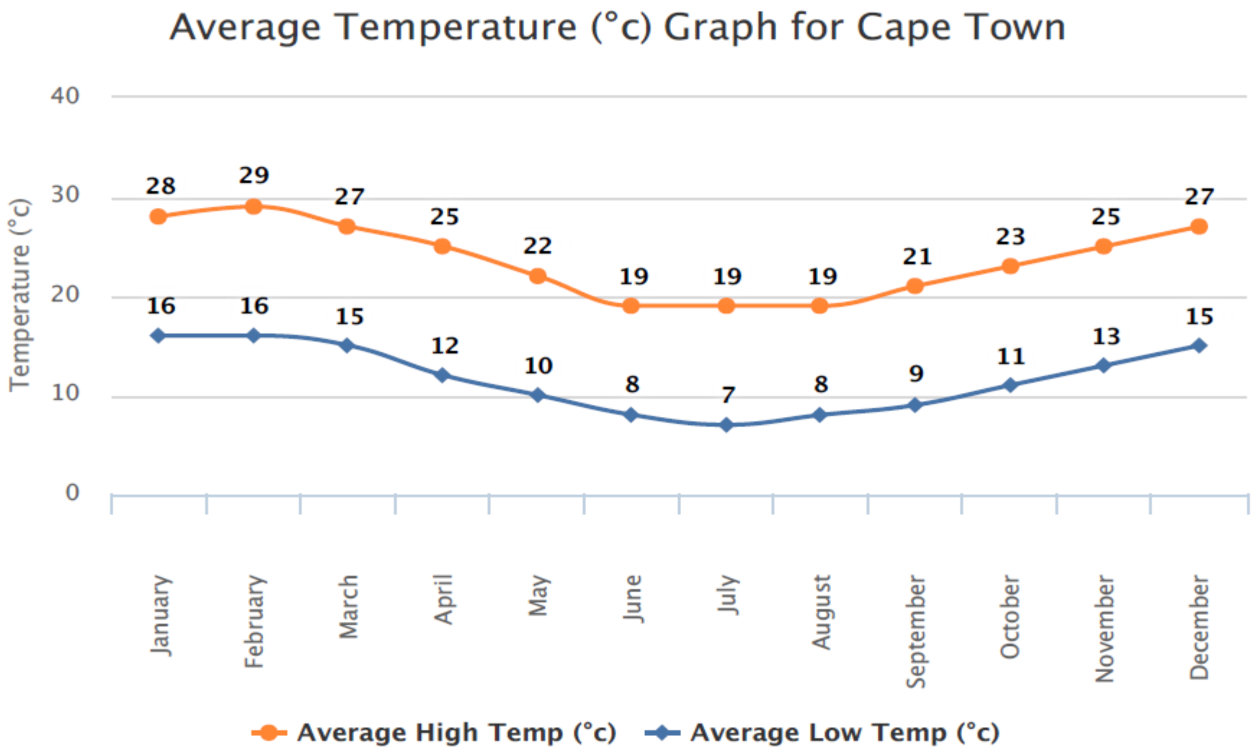


Figure 2-3: Average temperature in Cape Town (World weather, 2016)

2.9 Summary of Literature

The literature review started with the need for small scale anaerobic digestion, which provides biogas as an alternative decentralised energy source for lighting, heating and cooking with less harmful gases and particulates when compared to traditional fuels.

The anaerobic digestion process and the many factors affecting the process were then discussed. This dissertation aims to investigate the possibility of increasing the operating temperature of an anaerobic digester and its effect in increasing biogas production. However a review of the many factors affecting the anaerobic digestion process indicates how each anaerobic digestion system can vary relative to another system while operating at the same temperature.

The pH of the anaerobic digester as discussed in chapter 2.4.2 is an indication of how well the digester is operating. Literature shows that operating an anaerobic digester at a pH between 6.8 and 7.2 is the optimal pH for biogas production as various microbes responsible for the anaerobic digestion process are very active within this pH range. The pH of the digester can be used to control the operation and loading of the anaerobic digester.

Section 2.5 discussed typical biogas production yields and rates of production from anaerobic digesters using food waste. The reviewed literature suggest that the quantity of methane production from anaerobic digestion of food waste ranges between 435 and 489 mℓ/g VS added at temperatures above 30 °C after 25 to 40 days digestion.

The rate of biogas production also varies from system to system from 0.0016 to 0.9 litres of methane produced per day per litre of digester volume depending on the feed substrate at temperatures from 26 to 42 °C.

The studies and theory indicate that a 10 °C increase in anaerobic operating temperature could result in a 100 % increase in methane and biogas production.

The performance of the LMH anaerobic digester during a 10 week operating period produced on average enough biogas to cook for total of 2.5 hours per week. The digester consumed on average 46 kg of food per week and operated at temperatures between 14 - 20 °C.

The average annual temperature in Cape Town is about 17°C. With the LMH residence anaerobic digester installed below ground level and not insulated. The digester will be operating at ambient ground temperature throughout the year.

Reviewed studies report that the temperature of heated shower water leaving the shower drainage system is about 34 ° while the typical the shower temperature in the shower head is 40°C. Based on studied showering habits of South Africans, the volume of hot water leaving the LMH residence is estimated to be about 8.4 m^3 per day. This volume is more than 8 times the recommended maximum hydraulic loading for the digester installed at the LMH residence.

3 Research approach

This chapter presents the hypotheses of this dissertation, as well as the approach and methods used in order verify the hypotheses, including all experimental work and designs.

3.1 Hypothesis

Hypothesis 1:

The average temperature profile of the waste water leaving the LMH residence will have peaks in the morning and evening periods when the majority of students shower. The peak temperature periods will be in the morning before breakfast and in the evening after dinner. The temperature during these times is expected to be above 30 °C.

Hypothesis 2:

Adding a portion of this over 30 °C water into the LMH anaerobic digester will result in the digester running at 5 °C above the cold water operating temperature, and thus increase the productivity of the anaerobic digester.

3.2 Key Questions

1. How consistent are the temperature profiles from day to day for the waste water leaving LMH residence?
2. Are there differences in the temperature profiles between weekdays and weekends for the waste water leaving LMH residence?
3. What is average biogas production of the LMH digester when operated optimally but without warm water addition?
4. Is it technically feasible to use the heat from the LMH residence waste water pipeline to heat the digester?
5. What is the temperature increase relative to the cold water loading operating temperature of the LMH residence as a result of warm water addition?
6. What is the increase in biogas production as a result of the increased operating temperature of the LMH residence digester and how does it compare to theory?

3.3 Equipment, substrate and operation

The LMH residence anaerobic digester is located just behind the residence and is installed below ground level with the inlet and outlet chambers opening at ground level as shown in Figure 3-1.

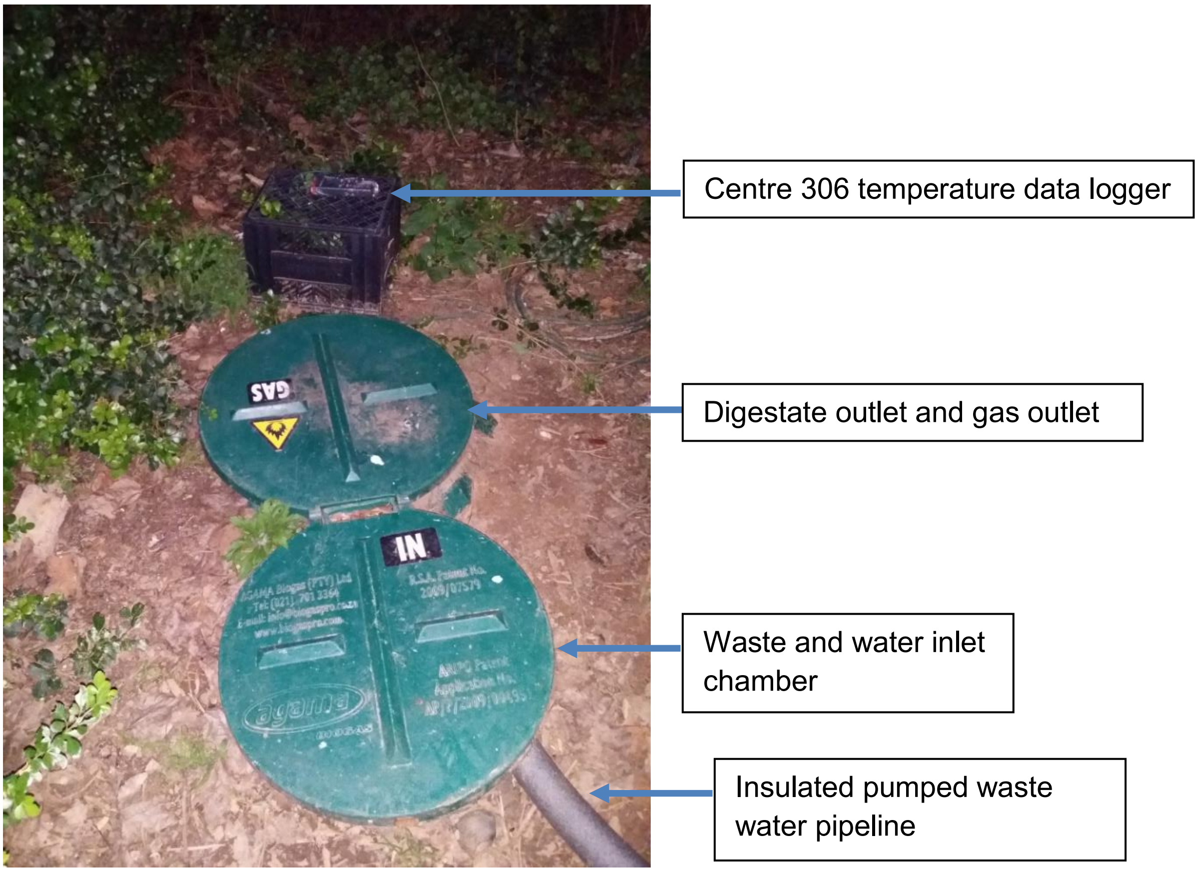


Figure 3-1: LMH anaerobic digester

The inlet chamber is opened to load the digester with food waste and water. Food waste is collected in the LMH residence kitchen, all paper and plastics are removed from the food waste before it is added to a 20 ℓ container. The mass of the food waste is measured using the kitchen scale and recorded, before it is added to the digester. The properties of food waste collected from the kitchen vary from day to day. The food waste is usually a mix of cooked rice, cereal, vegetables, meat, poultry and cooking oil.

The digester is loaded with food waste depending on the pH recorded in the outlet chamber of the digester and the methane composition of the biogas produced. In Chapter 2.4.2 the literature states that the optimum operating pH for a small scale anaerobic digester is 6.8 to 7.2, thus the LMH digester is operated to maintain or operate as close as possible to this pH range. The pH within the digester can be decreased by adding food waste as this increases the amount of hydrolysis reactions taking place within the digester. Alternatively if the pH drops below the desired minimum level, the digester will not be loaded with food waste as this allows the current methanogenic bacteria to increase the rate of methanogenesis reactions and as a result increase the pH. The digester pH is measured daily to determine if organic loading is needed. The pH within the digester is measured using a calibrated Crison pH meter shown in Figure 3-2.

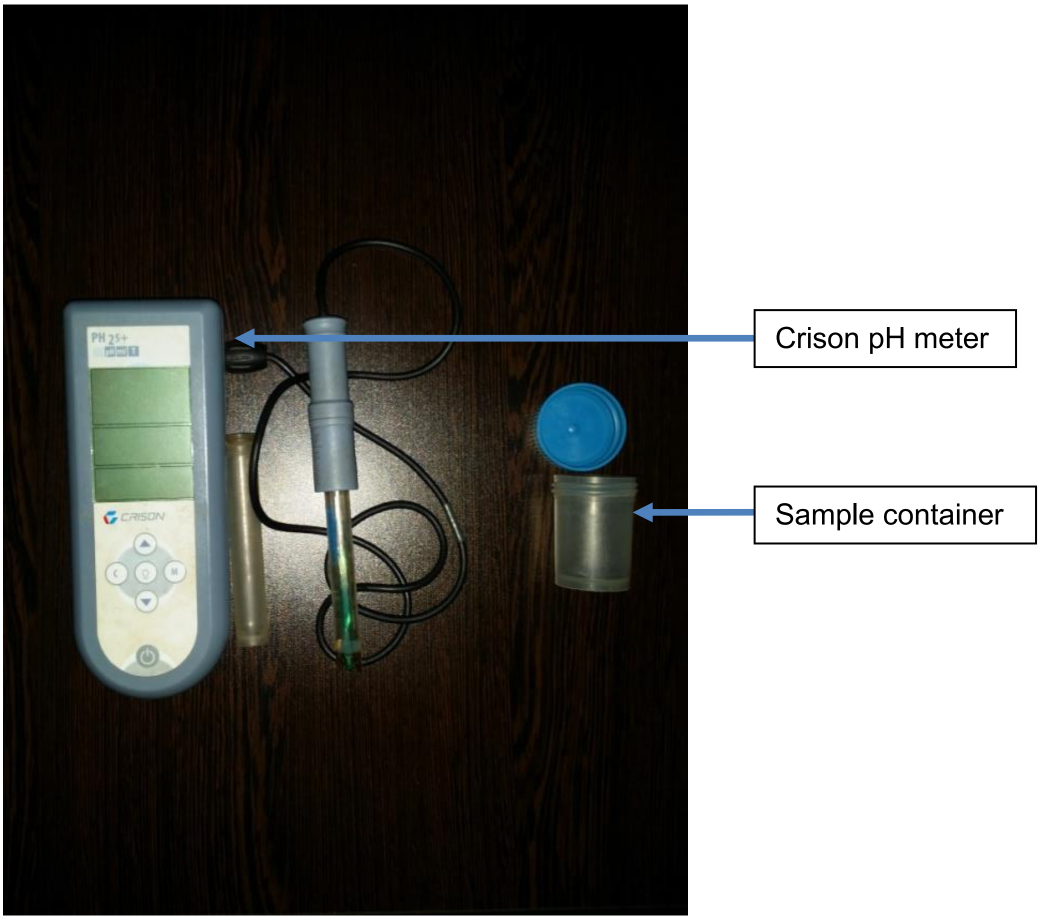


Figure 3-2: Crison pH meter and sample cup

A sample from the digester outlet chamber is collected using the sample container, the pH meter probe is inserted into the sample and the pH is measured. The measurement is done continuously until the same pH value is measured in 3 successive measurements, before the sample pH is recorded.

The methane content of the biogas produced is also a performance indicator of the anaerobic digester. If the methane content is 75 % or higher it means the methanogenic bacteria are producing high concentrations of methane and the pH in that area of the digester should be about 7 in order for this to occur. This indicates the digester should be loaded with organic waste. However if the methane concentration of the biogas produced is below 55%, the digester should not be loaded with organic waste. This allows time for the methanogenic bacteria to produce biogas with methane content in the range of 60 % to 74 %. The methane content of biogas and the pH are indicators of the stability of the anaerobic digester operation. If the digester is operating at a pH below 6.0 and producing biogas with methane content less than 55 % the digester should not be loaded with organic waste.

The biogas composition is recorded using the calibrated Riken Keiki GX-2012 (EX type A) gas composition meter as shown in Figure 3-3. The gas meter measures the methane, oxygen, carbon monoxide and hydrogen sulphide composition of the biogas. The gas pipeline is disconnected at the hob in the LMH residence kitchen, before the inlet of the gas meter is inserted into the biogas gas pipeline. Once the gas meter is switched on and the gas pipeline valve is opened. The gas meter records the composition of the biogas flowing though the meter. The measurements are recorded once the readings on the gas meter stabilize.

Figure 3-3: Riken Keiki GX-2012 gas composition meter

The gas pipeline from the digester into the kitchen has been installed with a PC50B-4B mechanical pressure gauge (0 to 100 mbar) supplied by Cape Instrument Services, and a model G1.6 calibrated gas volume meter supplied by ZHEJIANG CHINT INSTRUMENT & METER CO.,LTD as shown in Figure 3-4. The details of the gas volume meter are described in Appendix A. The burning of biogas takes place twice a day at 07:00 am and 03:00 pm.

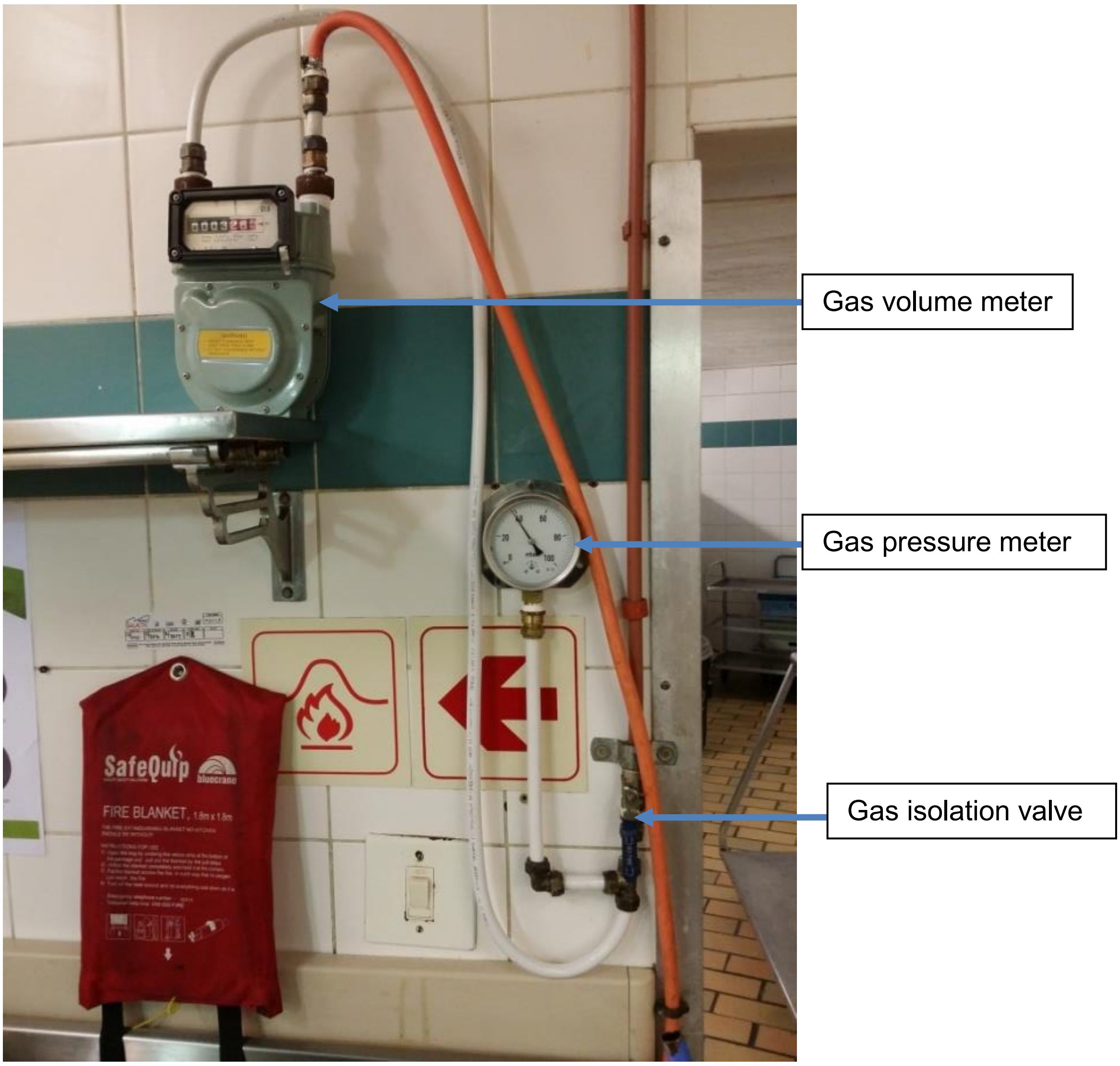


Figure 3-4: Gas pressure gauge and volume meter

Before the biogas is burnt for a particular day the hob valves are closed which allows the pressure gauge to read the static gas pressure in the digester. The gas pressure is then recorded and the volume meter reading is recorded. The gas composition is then also measured and recorded. The hob valves are then opened and the gas is burnt, the start time of burning is also recorded. Once the biogas pressure has been burned down to about 1 kPa, the hob valves are closed and the static pressure, volume meter reading and time are recorded. The static gas pressure difference, volume of gas burnt and time taken to burn the gas are then calculated and recorded.

The volume of gas burnt was previously calculated based on the pressure difference before and after burning of biogas (Naik et al, 2012), however with the installation of a calibrated gas volume meter the volume of gas burnt was measured directly.

3.4 Study design and execution

The key questions in chapter 3.2 will be analysed by setting up equipment to monitor the daily temperature profile of the waste water leaving the LMH residence and the quantity of biogas produced from the LMH digester. The description of the equipment and the methods for conducting the experiment is explained in this subsection.

3.4.1 Hot waste water measurements

The LMH residence waste water drain containing the waste water gravity sewer is located about 30 m from the LMH anaerobic digester. The temperature of the waste water leaving the LMH residence was recorded using a Type K thermocouple and a Centre 306 data-logger as shown in Figure 3-5. Mounting brackets were installed inside the drain to house the data logger and hold the probe end of the thermocouple inside the open pipe to record the temperature of the waste water leaving the LMH residence. The data-logger and thermocouple was setup to record the temperature of the waste water at one minute intervals continuously. The data was transferred from the data-logger on a daily basis to a laptop computer. The batteries within the data-logger were replaced every day by rechargeable 9V batteries.

The volume flow rate of hot waste water leaving the digester was also monitored at the times of the day when the waste water temperature was high relative to ambient temperature. The flow of waste water in the gravity sewer was visually observed during these times of high temperature. This was done to determine if the volume flow rate of warm waste water was suitable for use in the LMH anaerobic digester.

The waste water temperature profile was measured randomly during the months February, April, May and June to obtain temperature profiles of waste water leaving the LMH residence.

Figure 3-5: Thermocouple and data-logger

3.4.2 Digester performance

The standard performance of the anaerobic digester was obtained using food waste and cold tap water for the organic and hydraulic loading. The modified operation made use of the hot waste water leaving the LMH residence for hydraulic loading of the anaerobic digester.

3.4.2.1 Cold water operation

The standard operation of the anaerobic digester was the addition of food waste depending on the pH within the digester as described in Chapter 3.3. The hydraulic loading was done using cold tap water which is collected using a 20 ℓ container, the container is filled multiple times and the water is loading into the anaerobic digester. The temperature of the cold tap water varied slightly from day to day however was not measured as part of this research. The anaerobic digester reactor volume is 4 050 ℓ and the maximum hydraulic loading specified by the digester manufacturer is 1 000 ℓ per day or a 4 day hydraulic retention time. Literature in Chapter 2.5.2 indicates that an anaerobic digester operating on a hydraulic retention time of 10 days operates optimally using food waste at 50°C.

The operating hydraulic loading of the LMH digester was selected at 400 ℓ to 600 ℓ per day which is a hydraulic retention time (HRT) of 10 to 6.75 days respectively. The operating HRT is lower than the 25 to 40 days recommended in the literature. This is due to the design of the agama bio gas pro digester which retains most of the solids added to the digester, thus the digester can handle higher hydraulic loading rates, up to 1 000 ℓ per day as specified by the manufacturer.

For the cold water operation the digester was loaded with 400 ℓ of water per day during weeks 1 to 2 and 600 ℓ of water per day during weeks 3 to 4. The operating temperature profile of the digester was only measured during the last week of the cold water operation.

3.4.2.2 Warm water operation

The top water level of water within the waste water drain leaving LMH residence is lower than the top water level in the anaerobic digester. In order to transfer the warm water into the digester a pumped pipeline system was required. The design parameters for the piped system were determined as an input to the design, namely the volume flow rate required and the static head difference between the top water levels of the digester and the waste water in the gravity sewer.

The volume flow rate for the pumped system was determined based on the temperature profile of the waste water leaving the LMH residence and the flow profile of waste water leaving the LMH residence. The temperature profile in chapter 4.1.8 shows that the flow of warm waste water leaving the LMH residence on average is the highest in the morning between 06:25 am and 07:20 am from Monday to Friday. However on a particular day the peak flow can occur during a period as little as 30 minutes based on physical observations of the waste water leaving the LMH residence. The pump system design flow rate was selected based on pumping a volume of 600 ℓ in 30 minutes. The design flow rate is thus 20 ℓ per minute, as this is considered to be the largest volume required over the shortest available pumping time. The complete pump system design is attached in Appendix B.

The pipe selected was a 20 mm diameter polycarbonate pipe. The pipe was installed with 20 mm thick insulation around the pipe in order to minimise the heat lost from the piped warm water to the surroundings.

Overnight the ambient temperature decrease caused a decrease in the operating temperature of the digester as shown in figure 4-3. Thus loading of warm waste water in the early morning occurs when the digester is at its lowest temperature during the day. This is the most desirable time of the day for warm waste water hydraulic loading.

Figure 3-6 shows the installed submersible pump in the LMH residence waste water gravity sewer and Figure 3-7 shows the pump system operating.

Figure 3-6: Installed submersible pump in LMH residence waste water outlet drain

Figure 3-7: Operating submersible pump

The white PVC pipe has a flat disk mounted at the end of it in order to back up the flow onto the submersible pump set.

The power supply has also been installed with a programmable timer in order to automatically turn the pumped system on and off. The operation can be fully automated using the timer, and is shown in Figure 3-8.

Figure 3-8: Programmable timer

The digester was initially loaded with 400 ℓ per day in week 1 to 2, 500 ℓ per day in weeks 3 to 4, 600 ℓ per day weeks 5 to 6, 0 ℓ per day during week 7 and 600ℓ per day during week 8. The thermocouple and data logger used to monitor the temperature of the waste water leaving the LMH residence was also used to monitor the operating temperature of the digester during the warm waste water hydraulic loading period. The insulated pipe system is shown in Figure 3-9.

Figure 3-9: Insulated pipe from drain to LMH digester

4 Results and Discussions

4.1 Warm waste water leaving LMH residence

The first hypothesis of this dissertation states that "The temperature profile of the waste water leaving the LMH residence will have peaks in the morning and evening periods when majority of students shower. The peak temperature periods will be in the morning before breakfast and in the evening after dinner. The temperature during these times is expected to be above 30 °C".

The results of the temperature measurements for the waste water leaving LMH residence are presented and discussed in this section. Figures 10-1, 10-2, 10-3, 10-4, 10-5, 10-6 and 10-7 of Appendix C show the temperature profile of the waste water leaving the LMH residence on Mondays, Tuesdays, Wednesdays, Thursdays, Fridays, Saturdays and Sundays respectively.

4.1.1 Monday

The temperature profile of waste water leaving LMH residence for Monday 16th May and 6th June are plotted in Figure 10-1 of Appendix C. Between midnight and 06:00 am the temperature for 16th May remain relatively stable at about 22 °C while the temperature for 6th June peaks above 30 °C on four occasions for periods not more than 20 minutes. These small temperature increases could be due to a single individual using hot water. Then at about 06:10 am there is an increase in temperature for both days peaking to about 32 °C at 06:30 am and staying around the 30 °C temperature mark till about 08:00 am. Based on physical observations of the LMH residence waste water drain chamber, the period between 06:15 am and 07:15 am is when the flow rate of waste water is the highest. After 08:00 am the temperature decreases below 30 °C, there are peaks in the temperature over 30 °C for both days however these are for relatively short periods of time. A clear evening temperature peak is not observed for extended periods of time on these days.

4.1.2 Tuesday

The waste water temperature profile at LMH residence for Tuesday the 12th April, 19th April, 17th May and 7th June are plotted in Figure 10-2 in Appendix C. From midnight to 06:00 am there are temperature peaks above 30 °C for the 12th April, 19th April and 17th May, however these peaks do not last longer than 20 minutes. Both the 12th and 19th of April have temperature peaks above 30 °C between 05:25 am and 05:45 am. The morning temperature increases start at 06:00 am and by 06:30 am the temperature for all Tuesdays are above 30°C and remain there till about 07:30 am except for the 7th of June. This latter date, although during the term was after lectures had ended and examinations had started thus the students do not all shower before breakfast at the same time. There are again peaks above 30 °C throughout the day for the days analysed however none of the peaks last for more than 15 minutes, even after dinner there are no sustained temperature peaks above 30 °C. No evening temperature peak is observed.

4.1.3 Wednesday

The waste water temperature profile at LMH residence for Wednesday the 4th May, 11th May, 18th May and 8th June are plotted in Figure 10-3. From midnight to 06:00 am there are various temperature peaks above 30 °C for 11th and 18th of May however these peaks do not last longer than 10 minutes. At 06:00 am the temperature of the waste water starts to increases and by 06:30 am the temperature is above 30 °C and stays there till after 07:00 am. After 07:00 am there are temperature peaks above 30 °C however these peaks are for short periods not longer than 10 minutes. No clear evening temperature peak is observed.

4.1.4 Thursday

The waste water temperature profile at LMH residence for Thursday the 14th April, 21st April, 5th May and 2nd June are plotted in Figure 10-4. The temperature profile is similar to the Mondays, Tuesdays and Wednesdays in that there are localized peaks in temperature above 30 °C from midnight to 06:10 am. The 14th and 21st of April in particular have high peaks in the region of 34 °C however these peaks do not last longer than 20 minutes. At 06:20 am the temperature starts to increase and by 06:30 am the temperature for all days are all above 30 °C and stay there till after 07:10 am, except for the 2nd of June, which was after lectures had ended. After 07:10 am there are again peak temperatures above 30 °C however these peaks again last for short periods of time less than 20 minutes. The evening peak is again not observed.

4.1.5 Friday

The waste water temperature profile at LMH residence for Friday the 5th February, 6th May, 13th May and 3rd June are plotted in Figure 10-5. The temperature profile is similar to the previous weekdays. Localised peaks in waste water temperature above 30 °C are seen over short periods of time. At 06:07 am the temperature starts to increase above 30°C and stays there till 07:15 am except for Friday 3rd June, a date during the term but after lectures had ended. After 07:15 am there are again peaks in temperature above 30 °C however these peaks are for less than 20 minutes. Friday the 6th May does have peak waste water temperatures above 30 °C between 12:00 pm and 13:00 pm however this is the only day this peak is observed. The expected evening peak is again not observed for this data set.

4.1.6 Saturday

The waste water temperature profile at LMH residence for Saturday the 16th April, 23rd April and 4th June are plotted in Figure 10-6. The temperature profile is different to that of the weekdays as expected due to students not having to wake up and shower before lectures at 08h00. Morning peaks above 30 °C do occur however for short periods of time less than 15 minutes at random times of the day. Saturday 16th April shows a temperature increase above 30 °C at 07:00 am however before 07:20 am the temperature has decreased below 27 °C. The data for Saturdays show more random waste water temperature peaks when compared to the weekdays. The waste water temperature profile is less predictable on a Saturday when compared to weekdays.

4.1.7 Sunday

The waste water temperature profile at LMH residence for Sunday the 1st May and 8th May are plotted in Figure 10-7. The temperature from midnight to 06:00 am remains relatively stable until the first temperature peak occurs, all the temperature peaks throughout the day occur over periods less than 15 minutes in a random unpredictable manner. The data shows no sustained morning temperature peak as seen in the weekday data.

4.1.8 Weekday data

The weekday data shows a specific trend of temperature increase in the morning from 06:00 am to 07:30 am. The increase in temperature during this period is observed on all weekdays when lectures are taking place. Observations made during this time period at the LMH residence waste water gravity sewer indicate that the volume flow rate of waste water during this period is at its largest when compared to the rest of the day. This is due to the routine of the students, as every morning breakfast starts at 07:00 am and lectures start at 08:00 am. This causes majority students to have similar routines in the morning. Students wake up and shower between 06:00 am and 07:30 am in order to make it in time to have breakfast before the first lecture of the day starts.

Figure 4-1 shows the average weekday temperature profile of the waste water leaving LMH residence during term when lectures take place on campus. The graph shows the morning temperature peak clearly between 06:25 am and 07:20 am, with the average temperature during this time period measured at 30.5 °C. This is the optimum period to transfer the hot waste water from the drainage system to the LMH residence anaerobic digester to increase the operating temperature.

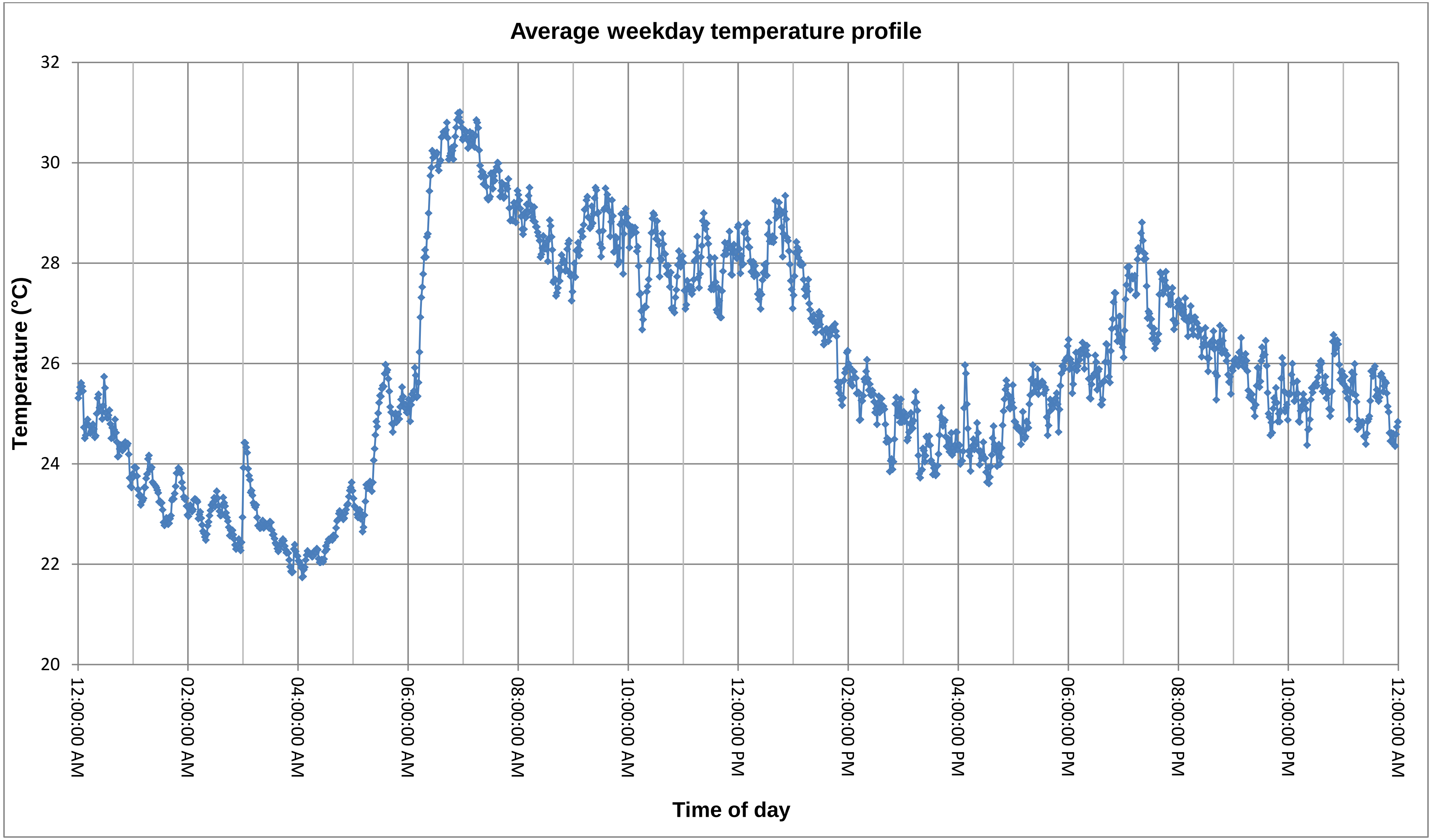


Figure 4-1: LMH residence waste water average weekday temperature profile

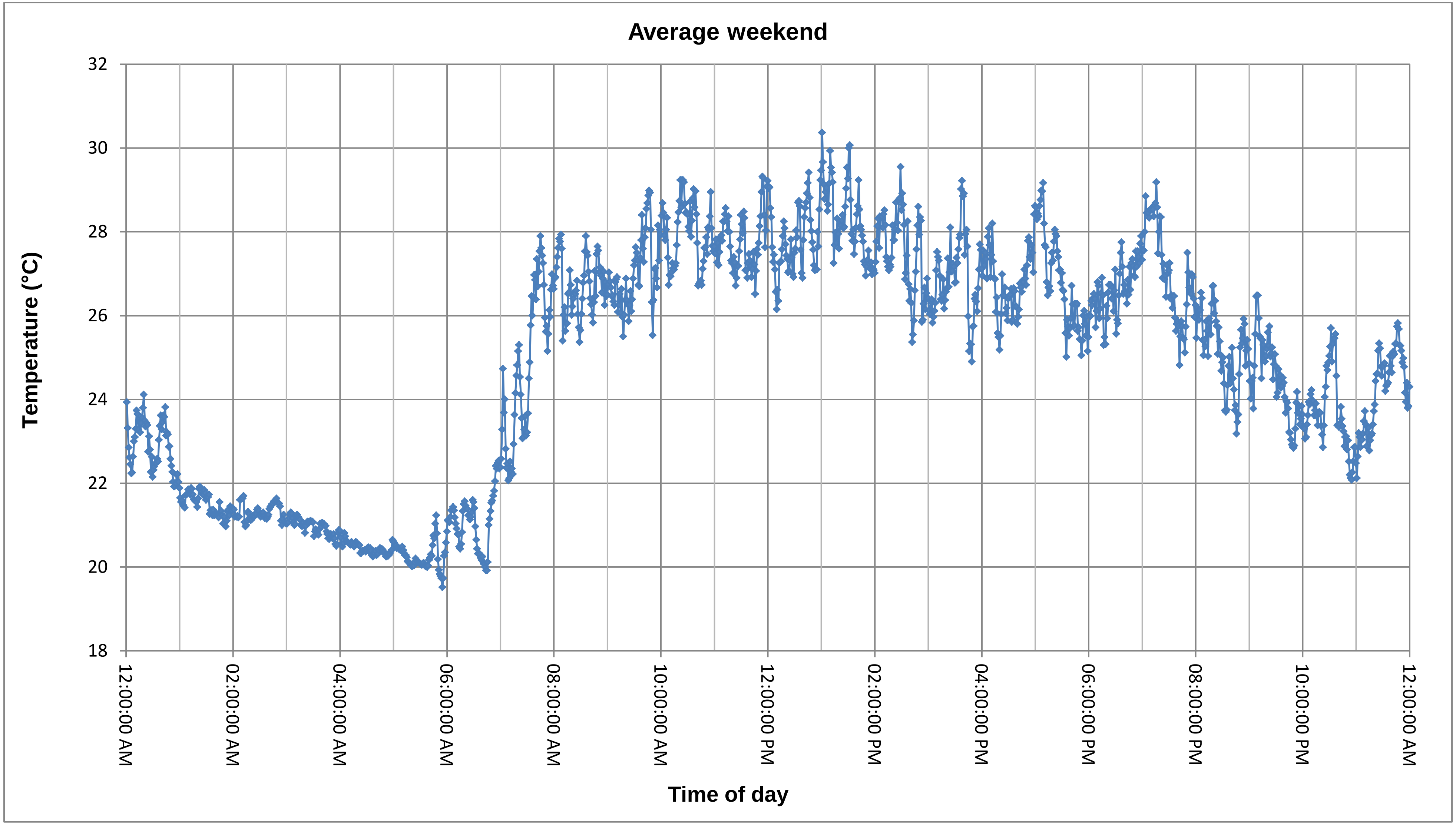


Figure 4-2: LMH waste water temperature profile average weekend

The graph does show an average temperature increase in the evening at 07:20 pm however it is relatively low in temperature at 28 °C and takes place over a short period of time less than 10 minutes. The weekday data proves hypothesis 1 however only for the morning peak in waste water temperature. The evening peak is not observed.

4.1.9 Weekend data

Based on the temperature data for Saturdays and Sundays hypothesis 1 does not hold for the weekends as students start their days at different times. The LMH residence waste water temperature profile is more random and unpredictable on the weekends. The Figure 4-2 shows the average temperature profile of the LMH residence waste water on the weekends. The graph shows no clear peak in temperature for a sustained period of time. Hypothesis 1 does not hold for the weekends however it does for weekday morning when lectures take place.

4.1.10 Key questions and hypothesis 1 overview

Key question 1 of Chapter 3.2 is concerned with how consistent the temperature profiles are from day to day. And question 2 interrogates whether there are differences in the temperature profiles between weekdays and weekends for the waste water leaving LMH residence.

Based on the data described in sections 4.1.1 to 4.1.9, weekday temperature profiles when lectures take place differ from weekend temperature profiles. Weekdays when lectures take place show the most consistent temperature profiles regarding the morning temperature peak above 30 °C. In the evenings, temperature is elevated too, but sustained peaks above 30 °C for these days are not observed.

During week days when lectures do not take place and weekend days, the morning temperature peak above 30 °C is not observed.

Hypothesis 1 is thus only valid for the mornings of weekdays when lectures take place.

4.2 Digester performance

This section presents and discusses the performance of the LMH anaerobic digester during the cold and warm waste water loading experiments. The operation and loading of the digester is first described. Results are then presented for a period during which cold tap water was used for hydraulic loading, to serve as the control in the experiment. The results obtained when warm waste water was fed by the pumped pipeline to the LMH anaerobic digester are presented thereafter.

4.2.1 Organic and hydraulic loading

The operation of the LMH anaerobic digester started during the month of March 2016. Table 4-1 shows the organic loading of wet mass from 14 March 2016 throughout the cold and warm water operation.

Table 4-1: Organic and hydraulic loading during operation

Period	Week	Organic loading (kg)	Hydraulic loading(ℓ)	Average pH
Start-up week 1	14/03/2016 - 20/03/2016	30	260	7.34
Start-up week 2	21/03/2016 - 27/03/2016	15	120	7.22
Start-up week 3	28/03/2016 - 03/04/2016	10	60	6.92
Start-up week 4	04/04/2016 - 10/04/2016	51	160	6.83
Start-up week 5	11/04/2016 - 17/04/2016	51	60	6.75
Start-up week 6	18/04/2016 - 24/04/2016	4	160	6.79
Start-up week 7	25/04/2016 - 01/05/2016	6	400	6.93
Start-up week 8	02/05/2016 - 08/05/2016	7.4	400	6.94
Start-up week 9	09/05/2016 - 15/05/2016	8.5	400	6.91
Start-up week 10	16/05/2016 - 22/05/2016	0	400	6.91
Start-up week 11	23/05/2016 - 29/05/2016	Sewage loaded into digester	0	6
Start-up week 12	30/05/2016 - 05/06/2016	0	400	5.64
Start-up week 13	06/06/2016 - 12/06/2016	0	500	5.99
Start-up week 14	13/06/2016 - 19/06/2016	0	500	6.38
Cold water week 1	20/06/2016 - 26/06/2016	10	2000	6.29
Cold water week 2	27/06/2016 - 03/07/2016	9	2000	6.30
Cold water week 3	04/07/2016 - 10/07/2016	12	3000	6.38
Cold water week 4	11/07/2016 - 17/07/2016	20	3000	6.63
Warm water week 1	18/07/2016 - 24/07/2016	10	2000	6.67
Warm water week 2	25/07/2016 - 31/07/2016	15	2000	6.70
Warm water week 3	01/08/2016 - 07/08/2016	12	2500	6.58
Warm water week 4	08/08/2016 - 14/08/2016	17	2500	6.69
Warm water week 5	15/08/2016 - 21/08/2016	20	3000	6.71
Warm water week 6	22/08/2016 - 28/08/2016	15	3000	6.59
Warm water week 7	29/08/2016 - 04/09/2016	11	0	6.61
Warm water week 8	05/09/2016 - 11/09/2016	19	3000	6.65

The LMH anaerobic digester was loaded with an average of 18.3 kg of organic food waste and 242 ℓ of cold water per week during the first 10 weeks of the start-up phase of operation. During these 10 weeks the digester was monitored to maintain stable operating pH between 6.8 and 7.

The discharge of the LMH anaerobic digester is connected to a gravity sewer pipeline. The operating water level within the LMH anaerobic digester is higher than the water level in sewage pipeline and as a result the digestate leaving digester gravitates into the sewage pipeline. However during week 11 of the start-up operation the LMH anaerobic digester was loaded with sewage waste water as a result of a sewage pipeline blockage upstream of the LMH anaerobic digester. This caused an overloading of organic waste to the anaerobic digester, however during weeks 12 to 14 of the start-up phase the digester pH started recovering and increasing to 6.38 during week 14. Organic loading of food waste resumed during week 1 of the cold water operation.

Organic loading during the cold water operation was on average 12.8 kg of food waste per week. The digester pH was monitored to ensure organic loading did not result in a decrease in operating pH during the next week. The digester pH steadily increased from 6.29 during week 1 of cold water operation to 6.63 during week 4 of cold water operation. The average methane content of biogas produced also increased from 55 % during week 1 to 64 % during week 4 of the cold water operation as seen in the next section of the chapter.

Organic loading during the warm water operation was on average 14.9 kg of food waste per week. This is higher than during the cold water operation due to the digester producing more biogas and methane during this operating period.

The loading of warm waste water could also provide additional organic loading and COD (chemical oxygen demand) however this was not measured during this experiment. The warm waste water is extracted when majority of students are showering in the morning. The additional COD is expected to be relatively low due to the high volumes of shower water diluting the organic sewage. Also the pump-set installed is also not capable of handling solids, thus the majority of organic matter that is present is not loaded to the anaerobic digester.

The digester was operated to always maintain the pH between 6.3 and 7. The average operating pH during the warm water operation was between 6.58 and 6.71, also the methane content of biogas produced was between 61% and 71% as described in the next chapter.

4.2.2 Cold water digester operation

The cold water operation of the LMH anaerobic digester is explained in chapter 3.4.2.1. The LMH anaerobic digester temperature was monitored during the cold water operation from 20th June to

17th of July 2016. The digester was loaded with 400 ℓ/day of cold water during weeks 1 - 2 and 600 ℓ/day of cold water during weeks 3 - 4. The operating temperature within the digester was only monitored during the final week of the cold water operation, due to the digester operating at a relatively constant daily temperature. The operating pH within the digester was maintained between 6.24 and 6.81 throughout the cold water operation period.

4.2.2.1 Cold water digester operation temperature profile

The digester operating temperature profiles during the final week of the cold water operation are shown in Figures 11-1 to 11-7 of Appendix D. The figures show that the maximum operating temperature difference within the anaerobic digester does not exceed 1 °C during the last week of the cold water operation.

The average digester operating temperature profile during the final week of cold water operation is shown in Figure 4-3. The average operating temperature in the digester drops after midnight to the lowest temperature of 14.9 °C between 02:00 am and 07:00 am. Once the sun rises the operating temperature in the digester starts to increase to 15.2 °C at 10:00 am, thereafter the temperature remains relatively constant till 3:00 pm. This reduced temperature increase could be due to the loading of cold water which takes place at 10:00 am every day. A sudden increase in temperature is observed between 03:00 pm and 04:00 pm to a maximum of 15.5 °C. This temperature increase coincides with the time of day the second volume of biogas is burnt for the day at 03:00 pm. The cause of this temperature increase could be due to the draw off of biogas from the digester which causes the mixing of digestate. The temperature then steadily decreases from 15.5 °C at 4pm to 15 °C at midnight. The average operating temperature in the digester during this week was 15.2 °C.

The temperature of the digester during cold water operation does not vary substantially throughout the day, on average it varies by a maximum of 0.7 °C. Due to the low temperature variation within the digester, the temperature measured at 10:00 am before organic and hydraulic loading takes place was used as the average operating temperature for that particular day during the cold water operating period. Figure 4-3 shows that at 10:00 am the average time of day temperature is 15.2 °C, which is equivalent to the 15.2 °C average operating temperature for the final week of the cold water operation period. The average operating temperatures during weeks 1, 2, 3 and 4 are 15.4, 15.1, 15.4 and 15.2 °C respectively, based on temperature measurements taken daily at 10:00 am.

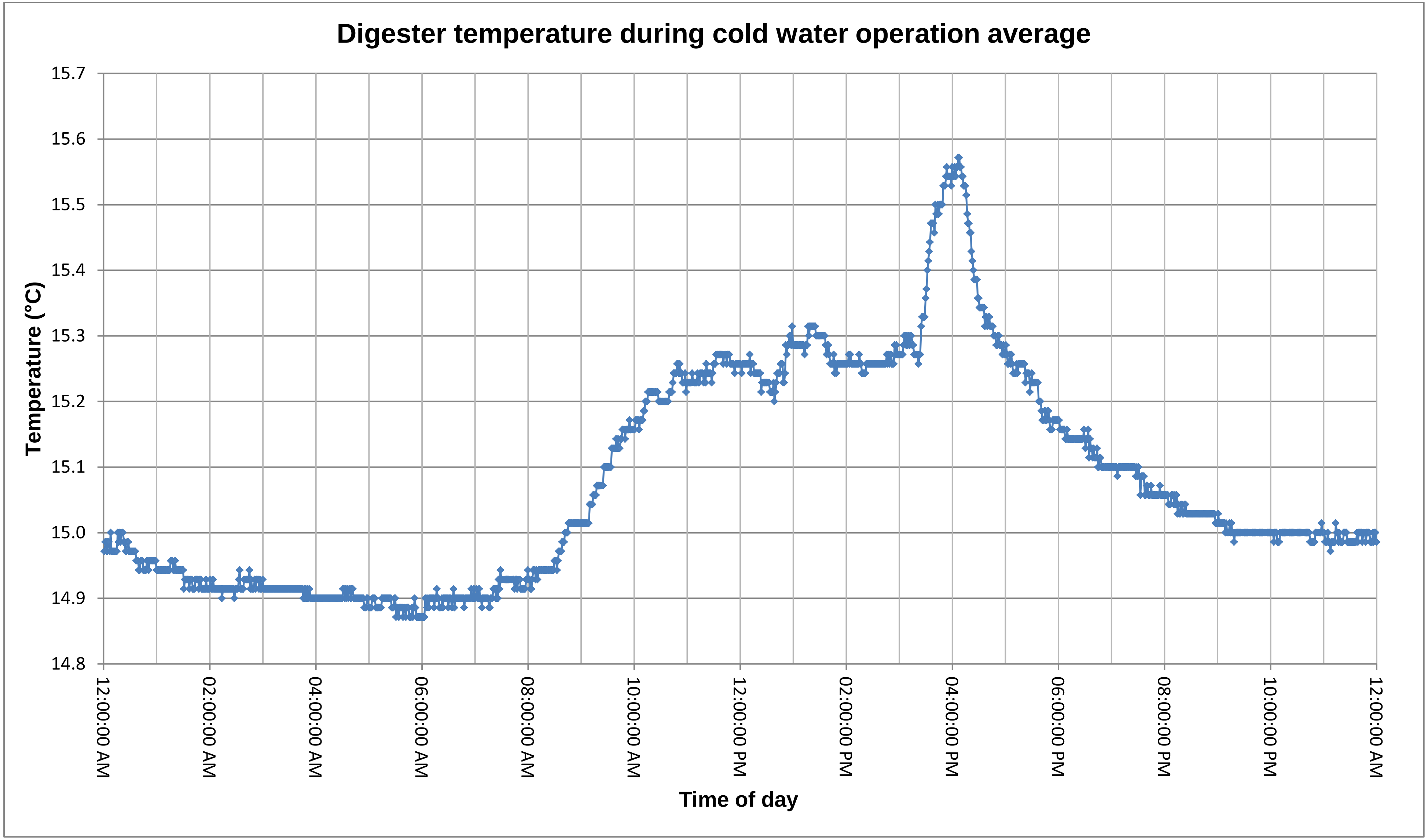


Figure 4-3: Average digester temperature during cold water operation

4.2.2.2 Cold water operation biogas production

The cold water operation of the anaerobic digester started with managing the organic loading and pH of the digester in order to stabilise it before data recording started. Once the digester was operating with stable biogas production and pH, data collection started. The data recording of hydraulic loading, biogas production, biogas composition, digester operating pH and digester operating temperature was recorded during the 4 weeks of cold water operation and are shown in detail in Appendix E. The data collected in the first 2 weeks is shown in Table 4-2 below, the average daily temperature is the temperature measured daily at 10:00 am.

Table 4-2: Cold water operation weeks 1-2

Week 1, 400ℓ cold water per day	**Methane content (%)**	**Volume of biogas burnt (m³)**	**Volume of methane burnt (m³)**	**pH**	**Average daily temperature**
20-Jun	55	0.055	0.030	6.42	15.7
21-Jun	54	0.054	0.029	6.3	15.8
22-Jun	54	0.056	0.030	6.24	15.4
23-Jun	55	0.055	0.030	6.26	15.2
24-Jun	56	0.055	0.031	6.29	15.6
25-Jun	56	0.056	0.031	6.27	14.9
26-Jun	56	0.057	0.032	6.25	15.1
Total		**0.388**	**0.214**		
Average	**55**	**0.055**	**0.031**	**6.29**	**15.4**
Week 2, 400ℓ cold water per day	**Methane content (%)**	**Volume of biogas burnt (m³)**	**Volume of methane burnt (m³)**	**pH**	**Average daily temperature**
27-Jun	57	0.06	0.034	6.24	14.8
28-Jun	56	0.056	0.031	6.3	15.1
29-Jun	57	0.059	0.034	6.34	14.7
30-Jun	57	0.061	0.035	6.32	15.3
01-Jul	58	0.058	0.034	6.28	15.2
02-Jul	58	0.06	0.035	6.33	15.5
03-Jul	58	0.057	0.033	6.32	15.1
Total		**0.411**	**0.235**		
Average	**57**	**0.059**	**0.034**	**6.30**	**15.1**

During week 1 of the cold water operation the digester produced a total of 0.388 m³ of biogas with a total methane content of 0.214 m³. The average methane content of the biogas produced was 55%. The average daily biogas and methane production was 0.055 and 0.031 respectively. The average operating temperature and pH for the week were 15.4 °C and 6.29 respectively.

During week 2 of cold water operation the digester produced a total of 0.411 m³ of biogas with a total methane content of 0.235 m³. The average methane content of biogas produced was 57%. The average daily biogas and methane production was 0.059 and 0.034 respectively. The average operating temperature and pH for the week were 15.1 °C and 6.30 respectively.

Table 4-3: Cold water operation weeks 3-4

Week 3, 600ℓ cold water per day	Methane content (%)	Volume of biogas burnt	Volume of methane burnt	pH	Average daily temperature
04-Jul	59	0.059	0.035	6.34	15
05-Jul	59	0.066	0.039	6.36	15.3
06-Jul	58	0.068	0.039	6.36	15.6
07-Jul	59	0.07	0.041	6.34	15.4
08-Jul	59	0.066	0.039	6.37	15.6
09-Jul	60	0.073	0.044	6.41	15.1
10-Jul	60	0.071	0.043	6.45	15.5
Total		**0.473**	**0.280**		
Average	**59**	**0.068**	**0.040**	**6.38**	**15.4**
Week 4, 600ℓ cold water per day	**Methane content (%)**	**Volume of biogas burnt**	**Volume of methane burnt**	**pH**	**Average daily temperature**
11-Jul	61	0.067	0.041	6.51	15.1
12-Jul	62	0.060	0.037	6.59	15.2
13-Jul	63	0.060	0.038	6.62	15.3
14-Jul	65	0.052	0.034	6.64	15.5
15-Jul	65	0.069	0.045	6.81	15.1
16-Jul	64	0.060	0.038	6.63	15.2
17-Jul	64	0.058	0.037	6.71	15.0
Total		**0.368**	**0.233**		
Average	**63**	**0.061**	**0.039**	**6.63**	**15.2**

Table 4-3 shows the data collected during weeks 3 and 4 of the cold water operating period. During week 3 the digester produced a total of 0.473 m³ of biogas with a total methane content of 0.280 m³. The average methane content of the biogas produced was 59 %. The average daily biogas and methane production was 0.068 and 0.040 respectively. The average operating temperature and pH for the week were 15.4 °C and 6.38 respectively.

During week 4 of cold water operation the digester produced a total of 0.368 m³ of biogas with a total methane content of 0.233 m³. The average methane content of biogas produced was 63 %. The average daily biogas and methane production was 0.061 and 0.039 respectively. The average operating temperature and pH for the week were 15.2 °C and 6.63 respectively.

The cold water operation took place during the months of June and July, which are the coldest months of the year in Cape Town. The average operating temperature of the anaerobic digester during the cold water operation period was 15.3 °C. The average weekly biogas and methane production during the cold water operation were 0.41 m³ and 0.214 m³ respectively, with an average methane content of 59%.

4.2.3 Warm water operation

The warm water operation of the LMH anaerobic digester is described in section 3.4.2.2. The digester was hydraulically loaded over a period of 8 weeks. The digester was loaded with warm waste water leaving the LMH residence using the pumped system as described in Appendix B. The operating temperature was measured every minute by the temperature data logger and thermocouple located at the discharge of the digester. Warm water hydraulic loading took place every week day between 06:00 am and 07:30 am.

The complete set of data recorded during the warm water operation period is attached in Appendix F. The temperature data in Appendix F is the average temperature calculated for a particular day, based on the 1 440 data measurements recorded every minute of the day.

4.2.3.1 Warm water operation temperature profile

During the warm water operating period the digester was loaded with different volumes of waste water every 2nd week. During weeks 1 and 2 of the warm water operating period the digester was loaded with 400 ℓ of warm waste water per day. The average week day operating temperature profile during weeks 1 and 2 of the warm water operating period is shown in Figure 4-4. The average temperature profile clearly shows the increase in operational temperature during the time period of hydraulic loading. From midnight to 06:00 am the digester temperature remains relatively constant just above 17.6 °C. The digester operating temperature on average increases by 2.4 °C between 06:00 am and 11:00 am as a result of the warm waste water loading. The temperature peaks at 19 °C by 11:00 am, then decreases steadily to midnight at 18.2 °C. The average operating digester temperature was calculated to be 17.6 °C for week 1 and 19.0 °C for week 2. The average operating temperature on the 1st day and 5th day of warm waste water hydraulic loading was 16.9 °C and 18.4 °C respectively. The operating temperature increase over the first 5 weekdays was 1.5 °C. Thereafter the temperature decreased over the weekend to 17.8 °C on Saturday and 17.3 °C on Sunday. Thus the average daily temperature decrease over the weekend of week 1 was 0.55 °C per day.

During weeks 3 and 4 of the warm water operation the digester was loaded with 500 ℓ of warm waste water a day. The average operating weekday temperature profile of the digester is shown in Figure 4-5. The temperature profile is different to that of the first 2 weeks of warm water operation. This is due to the digester temperature stabilizing from day to day during weeks 3 and 4 as opposed to increasing during the first 2 weeks. The average week day temperature profile from midnight to 06:00 am decreases steadily from 18.6 °C to 18.4 °C. The digester is then hydraulically loaded causing the average operating temperature to increases from 18.4 °C at 06:00 am to 19.4

°C by 10:30 am, this increase is lower compared to weeks 1 and 2. Thereafter the average temperature decreases slightly before increasing again to 19.5 °C at 12:30 pm. The temperature then decreases to 19.3 °C at 03:00 pm before increasing and peaking to 19.6 °C at 03:30 pm, as a result of biogas draw off from the digester. The temperature then decreases to 18.8 °C at midnight. The average operating temperature during both weeks 3 and 4 was calculated to be 18.9 °C confirming the operating temperature of the digester was stabilized. The average weekday daily digester temperature increase was calculated to be 0.18 °C for a particular week of warm water loading. The average weekend daily digester temperature decrease was calculated to be 0.56 °C per day slightly higher than weeks 1 and 2.

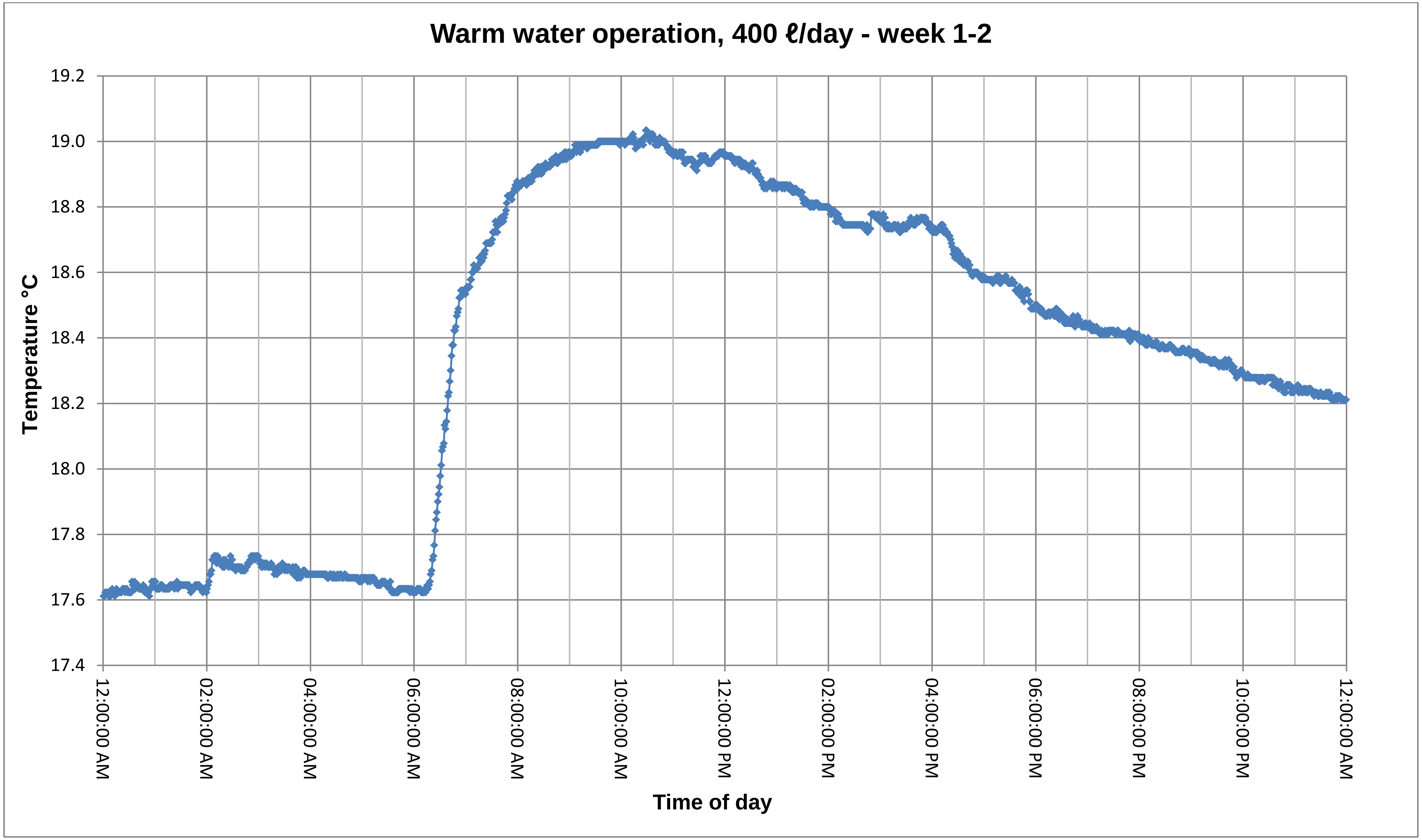


Figure 4-4: Warm water operation week 1-2

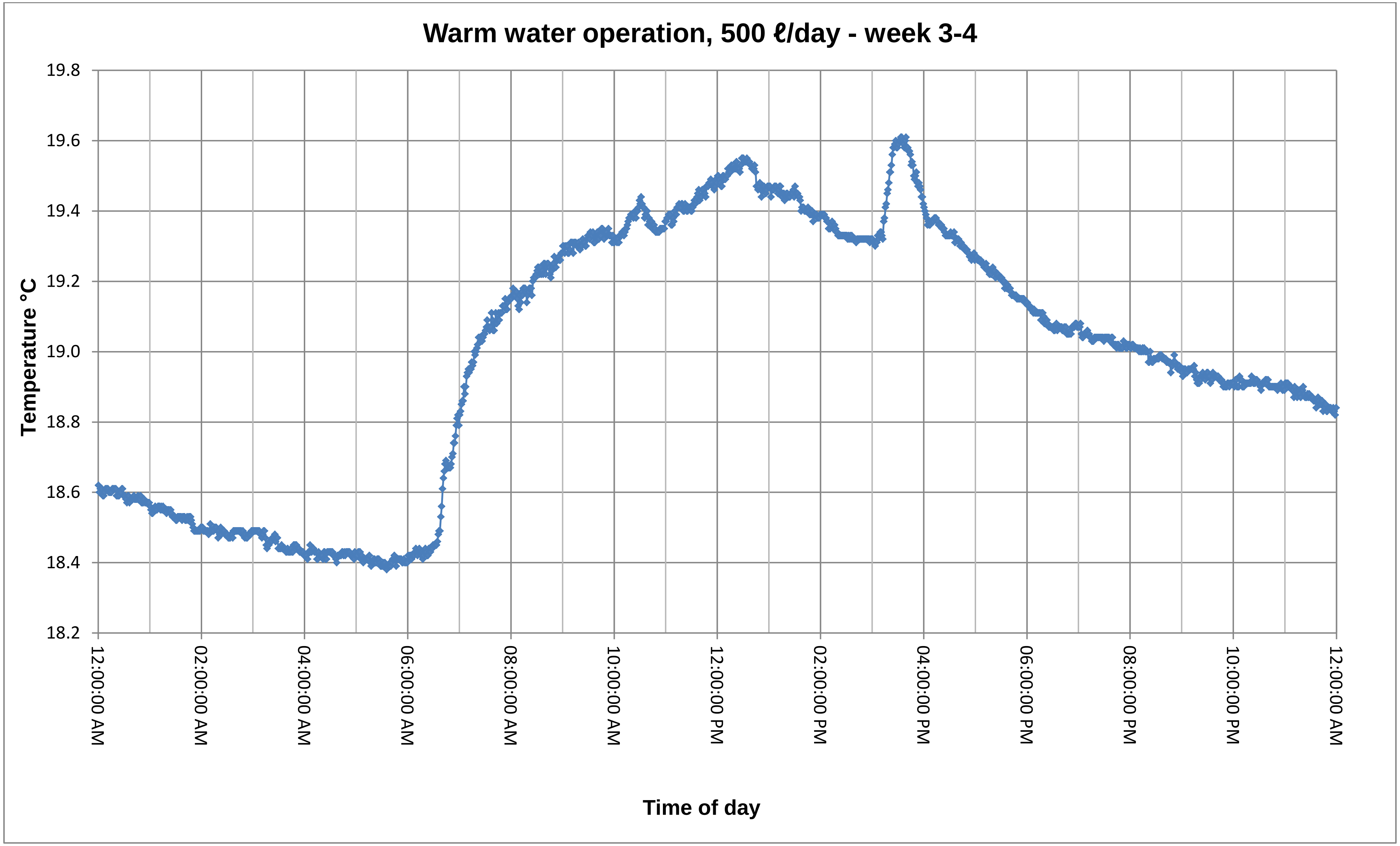


Figure 4-5: Warm water operation week 3-4

The average daily operating temperature profile of weeks 5 and 6 of the warm water operation is shown in Figure 4-6, and has a similar temperature profile to the pervious 4 weeks of the warm water operation. From midnight to 06:00 am the operating temperature decreases from 18.6 °C to 18.4 °C. The hydraulic loading at 06:00 am causes an increase in the average weekday operating temperature from 18.4 °C at 06:00 am to 20.6 °C by 10:10 am. The temperature remains relatively constant at 20.6 °C till 02:00 pm, when a slight decrease and increase in temperature is observed between 02:00 pm and 04:00 pm. The average weekday temperature then drops steadily from 20.4 °C at 04:00 pm to 20 °C at midnight. The average digester operating temperature during weeks 5 and 6 of the warm water operation was calculated at 19.7 °C and 20.2 °C respectively. The operating temperature throughout the 2 weeks varied between 18.3 °C and 20.4 °C.

During week 7 of the warm water operation no hydraulic loading took place. The average daily operating temperature profile is shown in Figure 4-7. The average operating temperature during this week was calculated to be 18.5 °C. The average operating temperature remained above 18 °C which is higher than any of the cold water operation days. The average temperature on the first and last days of no hydraulic loading was 20.1 °C and 17.7 °C respectively. The average operating temperature decreased by 2.4 °C during the week of no warm waste water loading. This demonstrates the heat losses from the digester when operating at ambient temperature.

Week 8 was the final week of warm water loading and the digester was loaded with 600 ℓ per day. The average weekday digester operating temperature profile is shown in Figure 4-8. From midnight to 07:00 am the average digester operating temperature remained constant at 19 °C. Thereafter the hydraulic loading causes an increase in temperature from 19 °C to 20.3 °C by 09:00 am. The operating temperature remains constant at 20.3 °C till 02:00 pm when the digester temperature increases and peaks to 20.7 °C at 02:18 pm. Thereafter the operating temperature decreases to 19.7 °C at midnight. The average operating temperature during this week was calculated to be 20 °C. The operating temperature increased from 17.7 °C on Sunday 4th September 2016 to 20.9 °C on Friday 9th September, a total increase of 3.2 °C over 5 days of warm waste water loading.

The digester warm water operation period showed an increase in average digester operating temperature from 15.3 °C for the cold water operation to 19.2 °C for the warm water operation. The increase in average digester operating temperature of 3.9 °C was achieved as a result of hydraulic loading using warm waste water. The maximum average weekly operating temperature obtained as a result of hydraulic loading using warm waste water was 20.2 °C which was about 5 °C higher than the average operating temperature during the cold water operating period. The cold water operation was during June and July when the ambient temperature was generally lower than the warm water operation period, which could result in marginally more heat loss during the cold water operation.

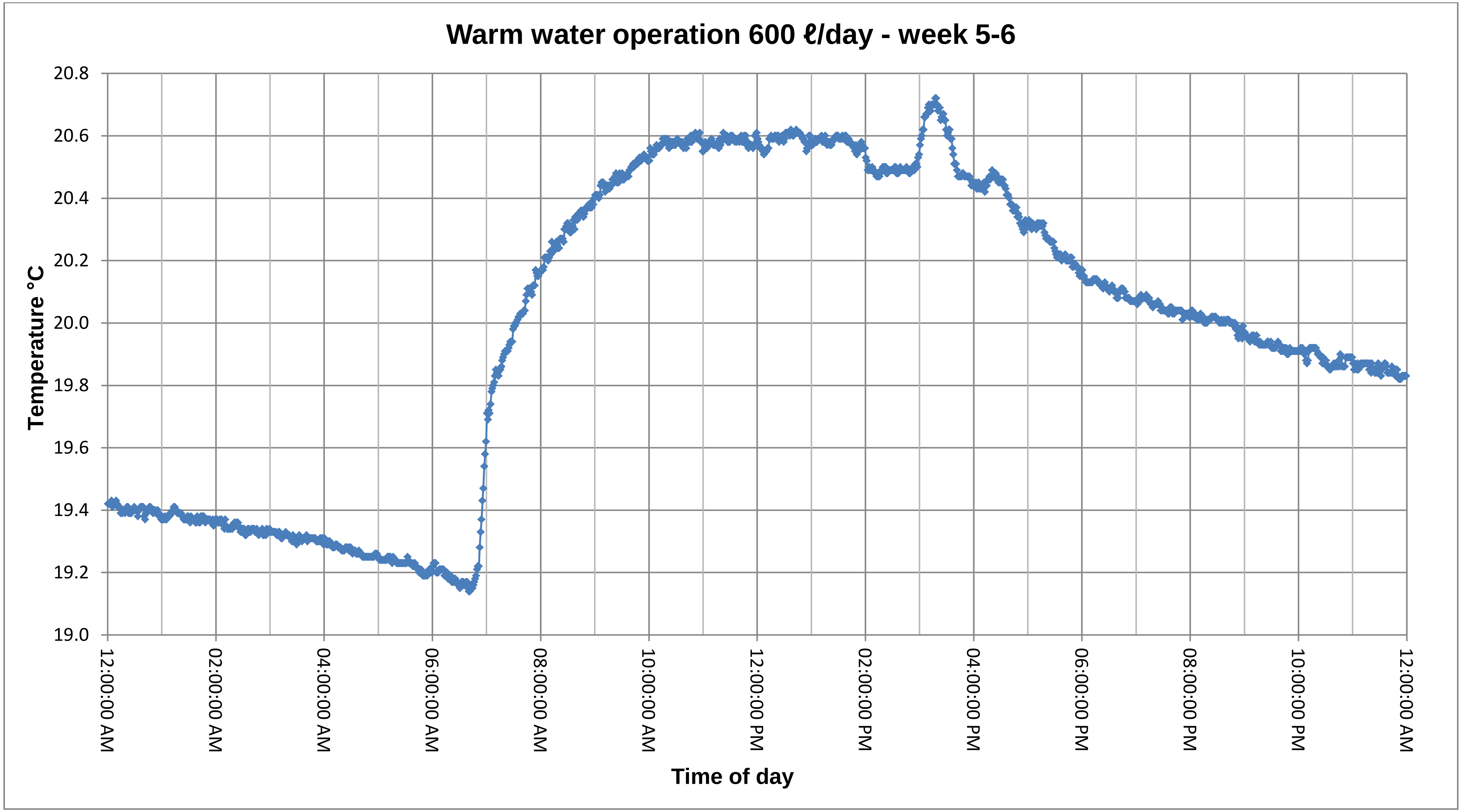


Figure 4-6: Warm water operation weeks 5-6

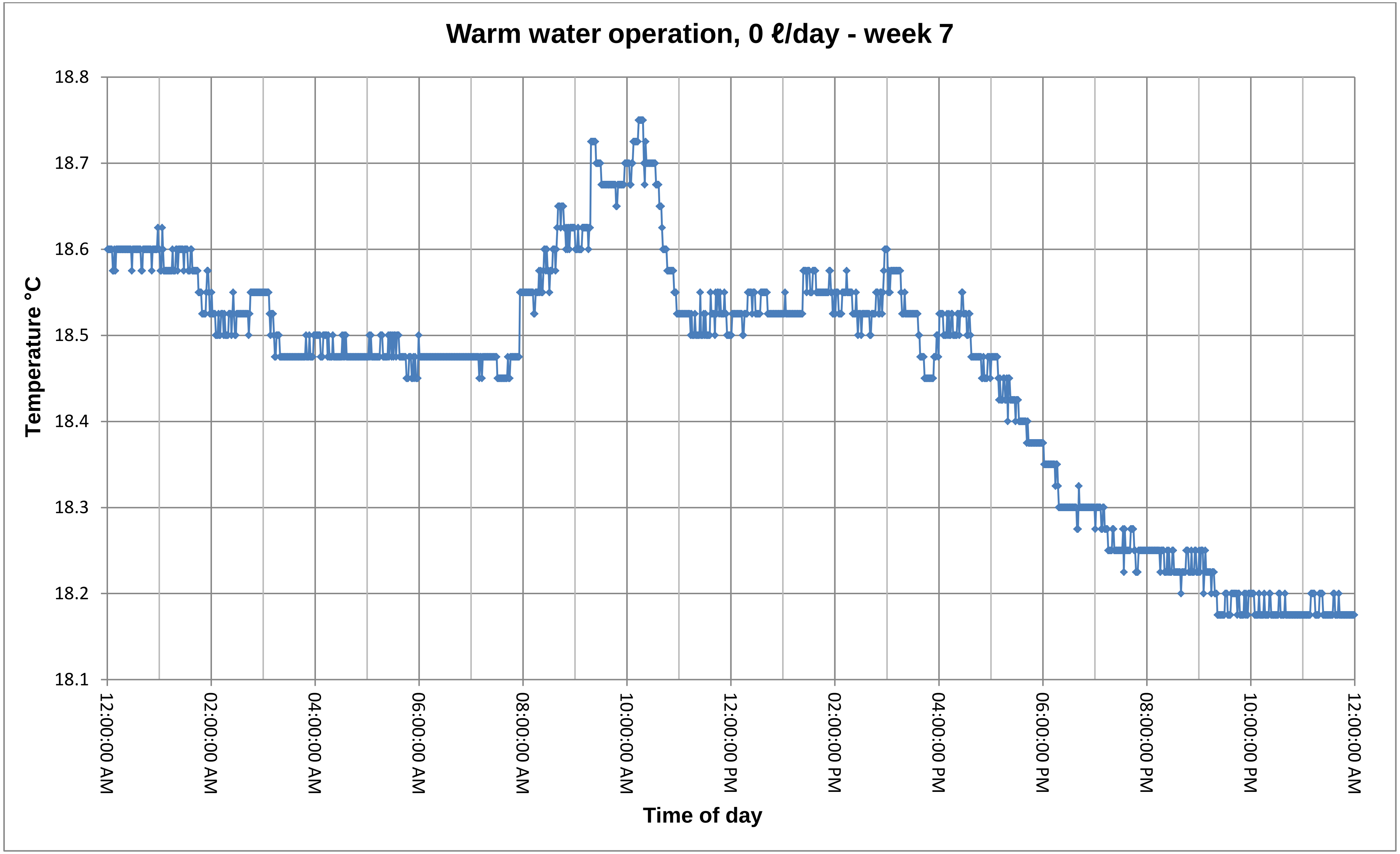


Figure 4-7: Warm water operation week 7

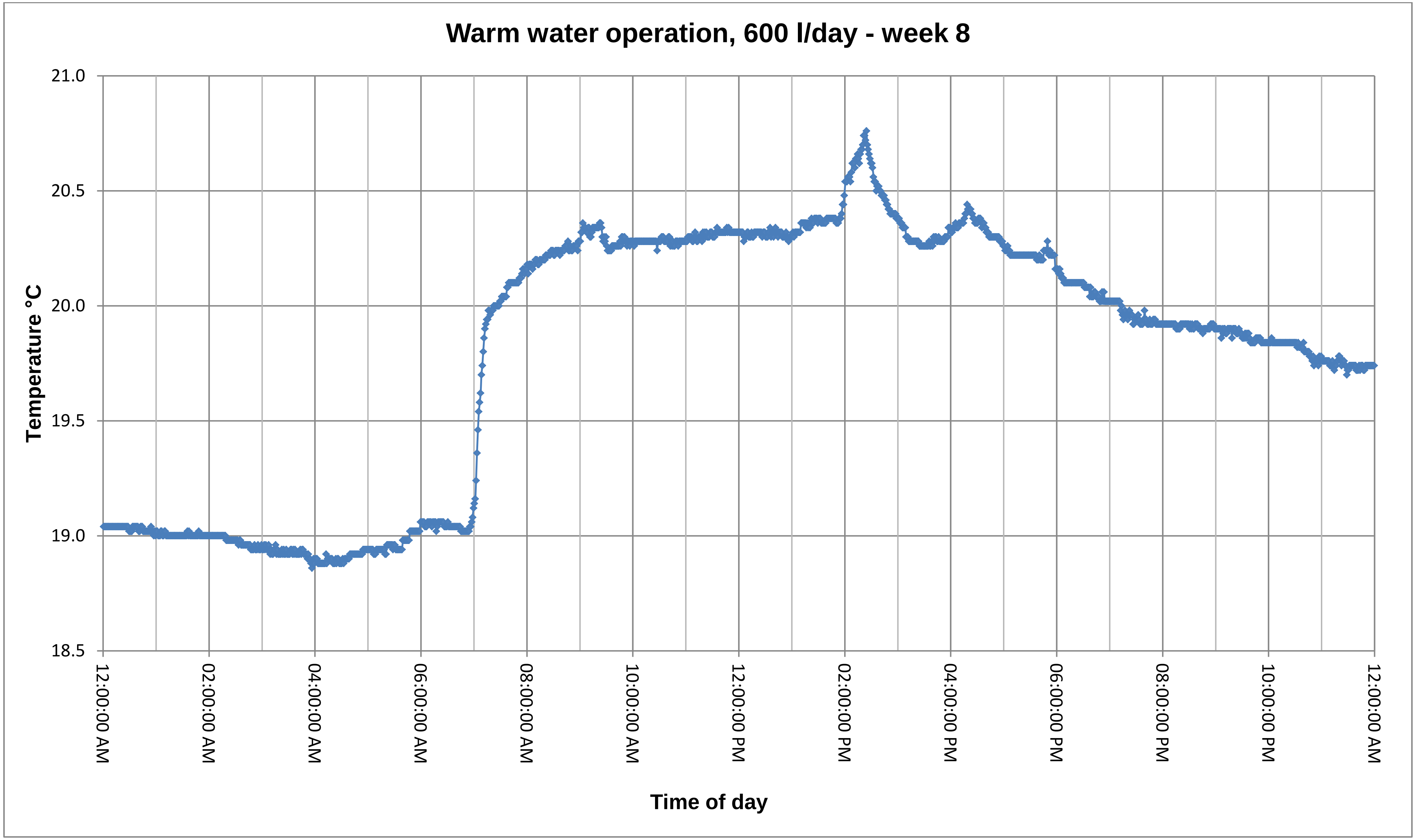


Figure 4-8: Warm water operation week 8

4.2.3.2 Warm water operation digester performance

The data recording of hydraulic loading, biogas production, biogas composition, digester operating pH and digester operating temperature was recorded during the 8 weeks of warm water operation. All data collected is shown in Appendix F, the data collected in the first 2 weeks of the warm water operation is shown in Table 4-4. The average daily temperature was calculated using the data collected by the temperature data logger.

Table 4-4: Warm water operation weeks 1-2

Week 1, 400ℓ warm water per day	**Methane content (%)**	**Volume of biogas burnt (m³)**	**Volume of methane burnt (m³)**	**pH**	**Average daily temperature**
18-Jul	65	0.091	0.059	6.73	16.9
19-Jul	65	0.064	0.042	6.66	16.8
20-Jul	72	0.053	0.038	6.64	17.7
21-Jul	72	0.052	0.037	6.7	18.2
22-Jul	73	0.067	0.049	6.68	18.4
23-Jul	68	0.087	0.059	6.58	17.8
24-Jul	70	0.07	0.049	6.72	17.3
Total		**0.484**	**0.333**		
Average	**69**	**0.069**	**0.048**	**6.67**	**17.6**
Week 2, 400ℓwarm water per day	**Methane content (%)**	**Volume of biogas burnt (m³)**	**Volume of methane burnt (m³)**	**pH**	**Average daily temperature**
25-Jul	74	0.066	0.049	6.72	18
26-Jul	68	0.11	0.075	6.68	18.4
27-Jul	70	0.088	0.062	6.74	18
28-Jul	71	0.09	0.064	6.69	19.7
29-Jul	74	0.075	0.055	6.7	20.3
30-Jul	74	0.085	0.063	6.76	19.6
31-Jul	75	0.084	0.063	6.6	18.8
Total		**0.598**	**0.431**		
Average	**72**	**0.085**	**0.062**	**6.70**	**19.0**

During week 1 of the warm water operation the digester produced a total of 0.484 m³ of biogas with a total methane content of 0.333 m³. The average methane content of the biogas produced was 69 %. The average daily biogas and methane production were 0.069 m³ and 0.048 m³ respectively. The average operating temperature and pH for the week were 17.6 °C and 6.67 respectively. The average digester operating temperature increased by 2.4 °C relative to the previous week of cold water operation.

During week 2 of the warm water operation the digester produced a total of 0.598 m³ of biogas with a total methane content of 0.431 m³. The average methane content of the biogas produced was 72 %. The average daily biogas and methane production were 0.085 m³ and 0.062 m³ respectively.

The average operating temperature and pH for the week were 19 °C and 6.7 respectively. The average digester operating temperature increased by 1.4 °C relative to the first week of warm water operation.

Table 4-5: Warm water operation weeks 3-4

Week 3, 500ℓ warm water per day	**Methane content (%)**	**Volume of biogas burnt (m^3)**	**Volume of methane burnt (m^3)**	**pH**	**Average daily temperature**
01-Aug	75	0.085	0.064	6.56	18.9
02-Aug	75	0.062	0.047	6.54	19.4
03-Aug	74	0.082	0.061	6.57	18.7
04-Aug	74	0.068	0.050	6.68	18.9
05-Aug	77	0.093	0.072	6.6	19.2
06-Aug	76	0.118	0.090	6.58	18.8
07-Aug	77	0.071	0.055	6.56	18.2
Total		**0.579**	**0.437**		
Average	**75**	**0.083**	**0.062**	**6.58**	**18.9**
Week 4, 500ℓ warm water per day	**Methane content (%)**	**Volume of biogas burnt (m^3)**	**Volume of methane burnt (m^3)**	**pH**	**Average daily temperature**
08-Aug	75	0.096	0.072	6.63	18.5
09-Aug	77	0.101	0.078	6.66	18.3
10-Aug	76	0.102	0.078	6.77	18.9
11-Aug	78	0.113	0.088	6.7	19.4
12-Aug	76	0.093	0.071	6.7	19.6
13-Aug	77	0.128	0.099	6.65	19
14-Aug	76	0.132	0.100	6.69	18.3
Total		**0.765**	**0.585**		
Average	**76**	**0.109**	**0.084**	**6.69**	**18.9**

Table 4-5 shows the data collected during weeks 3 and 4 of the warm water operation. During week 3 of the warm water operation the digester produced a total of 0.579 m^3 of biogas with a total methane content of 0.437 m^3. The average methane content of the biogas produced was 75 %. The average daily biogas and methane production were 0.083 m^3 and 0.062 m^3 respectively. The average operating temperature and pH for the week were 18.9 °C and 6.56 respectively. The average digester operating temperature remained relatively constant to the previous week of warm water operation.

During week 4 of the warm water operation the digester produced a total of 0.765 m^3 of biogas with a total methane content of 0.585 m^3. The average methane content of the biogas produced was 76 %. The average daily biogas and methane production were 0.109 m^3 and 0.084 m^3 respectively. The average operating temperature and pH for the week were 18.9 °C and 6.69 respectively. The average digester operating temperature remained relatively constant to the previous week of warm water operation.

Table 4-6: Warm water operation weeks 5-6

Week 5, 600ℓ warm water per day	Methane content (%)	Volume of biogas burnt (m³)	Volume of methane burnt (m³)	pH	Average daily temperature
15-Aug	75	0.114	0.085	6.71	18.7
16-Aug	77	0.126	0.097	6.65	19.4
17-Aug	77	0.12	0.092	6.7	20
18-Aug	74	0.135	0.100	6.8	20.2
19-Aug	74	0.144	0.107	6.8	20.2
20-Aug	70	0.166	0.116	6.63	20
21-Aug	65	0.188	0.122	6.65	19.1
Total		**0.993**	**0.720**		
Average	**73**	**0.142**	**0.103**	**6.71**	**19.7**
Week 6, 600ℓ warm water per day	**Methane content (%)**	**Volume of biogas burnt (m³)**	**Volume of methane burnt (m³)**	**pH**	**Average daily temperature**
22-Aug	62	0.148	0.092	6.6	19.5
23-Aug	62	0.152	0.094	6.56	20
24-Aug	61	0.143	0.087	6.53	20.3
25-Aug	61	0.206	0.126	6.51	20.5
26-Aug	61	0.189	0.115	6.62	20.9
27-Aug	61	0.201	0.123	6.66	20.4
28-Aug	61	0.147	0.090	6.65	19.7
Total		**1.186**	**0.726**		
Average	**61**	**0.169**	**0.104**	**6.59**	**20.2**

Table 4-6 shows the data collected during weeks 5 and 6 of the warm water operation. During week 5 of the warm water operation the digester produced a total of 0.993 m³ of biogas with a total methane content of 0.720 m³. The average methane content of the biogas produced was 73 %. The average daily biogas and methane production were 0.142 m³ and 0.103 m³ respectively. The average operating temperature and pH for the week were 19.7 °C and 6.71 respectively. The average digester operating temperature increased by 0.9 °C relative to the previous week of warm water operation.

During week 6 of the warm water operation the digester produced a total of 1.186 m³ of biogas with a total methane content of 0.726 m³. The average methane content of the biogas produced was 61 %. The average daily biogas and methane production were 0.169 m³ and 0.104 m³ respectively. The average operating temperature and pH for the week were 20.2 °C and 6.59 respectively. The average digester operating temperature increased by 0.5 °C relative to the previous week of warm water operation.

Table 4-7: Warm water operation weeks 7-8

Week 7, no warm water	Methane content (%)	Volume of biogas burnt (m^3)	Volume of methane burnt (m^3)	pH	Average daily temperature
29-Aug	62	0.17	0.105	6.59	20.1
30-Aug	62	0.19	0.118	6.61	19.2
31-Aug	63	0.183	0.115	6.61	18.5
01-Sep	62	0.151	0.094	6.59	18.2
02-Sep	63	0.138	0.087	6.64	17.9
03-Sep	63	0.097	0.061	6.61	17.8
04-Sep	64	0.154	0.099	6.62	17.7
Total		**1.083**	**0.679**		
Average	**63**	**0.155**	**0.097**	**6.61**	**18.5**
Week 8, 600ℓ warm water per day	**Methane content (%)**	**Volume of biogas burnt (m^3)**	**Volume of methane burnt (m^3)**	**pH**	**Average daily temperature**
05-Sep	64	0.181	0.116	6.6	18.2
06-Sep	64	0.134	0.086	6.75	19.2
07-Sep	63	0.192	0.121	6.74	20.1
08-Sep	62	0.173	0.107	6.71	20.6
09-Sep	62	0.25	0.155	6.57	20.9
10-Sep	62	0.226	0.140	6.62	20.7
11-Sep	62	0.228	0.141	6.54	20.1
Total		**1.384**	**0.866**		
Average	**63**	**0.198**	**0.124**	**6.65**	**20.0**

Table 4-7 shows the data collected during weeks 7 and 8 of the warm water operation. During week 7 of the warm water operation the digester produced a total of 1.083 m^3 of biogas with a total methane content of 0.679 m^3. The average methane content of the biogas produced was 63 %. The average daily biogas and methane production were 0.155 m^3 and 0.093 m^3 respectively. The average operating temperature and pH for the week were 18.5 °C and 6.61 respectively. The average digester operating temperature decreased by 1.7 °C relative to the previous week of warm water operation. The decrease in temperature is due to the lack of warm waste water hydraulic loading.

During week 8 of the warm water operation the digester produced a total of 1.384 m^3 of biogas with a total methane content of 0.866 m^3. The average methane content of the biogas produced was 63 %. The average daily biogas and methane production were 0.198 m^3 and 0.124 m^3 respectively. The average operating temperature and pH for the week were 20.0 °C and 6.65 respectively. The average digester operating temperature increased by 1.5 °C relative to the previous week of warm water operation.

4.2.4 Digester performance comparison between cold and warm water operation

The average operating temperature during the cold water operation of the LMH anaerobic digester was 15.3 °C while the average operating temperature during the warm water operation was 19.2 °C. The average operating temperature increase achieved by hydraulic loading of warm waste water was 3.9 °C. Figure 4-9 shows the average operating and ambient temperatures during the 12 weeks of operation. The detailed ambient temperature data is attached in Appendix G. Weeks 1 to 4 represent the first 4 weeks of the cold water operation and weeks 5 to 12 represent weeks 1 to 8 of the warm water operation. The weeks 1 to 4 of the cold water operation shows a relatively constant operating temperature at 15.3 °C, even though the hydraulic loading differs between weeks 1 to 2 and 3 to 4 by 200 ℓ per day. The hydraulic loading during the cold water operation does not affect the operating temperature of the digester substantially, as both the digester and cold water are at below ground level ambient temperature.

The first week of the warm water operation (week 5) shows a significant increase in the average operating temperature from 15.2 °C to 17.6 °C. The operating temperature of week 6 again shows an increase in operating temperature to 19 °C even though the warm waste water hydraulic loading is the same at 400 ℓ per day. The increase in weekly average operating temperature while the digester is loaded with the same thermal load is due to the digester retaining thermal heat from the previous week of thermal loading.

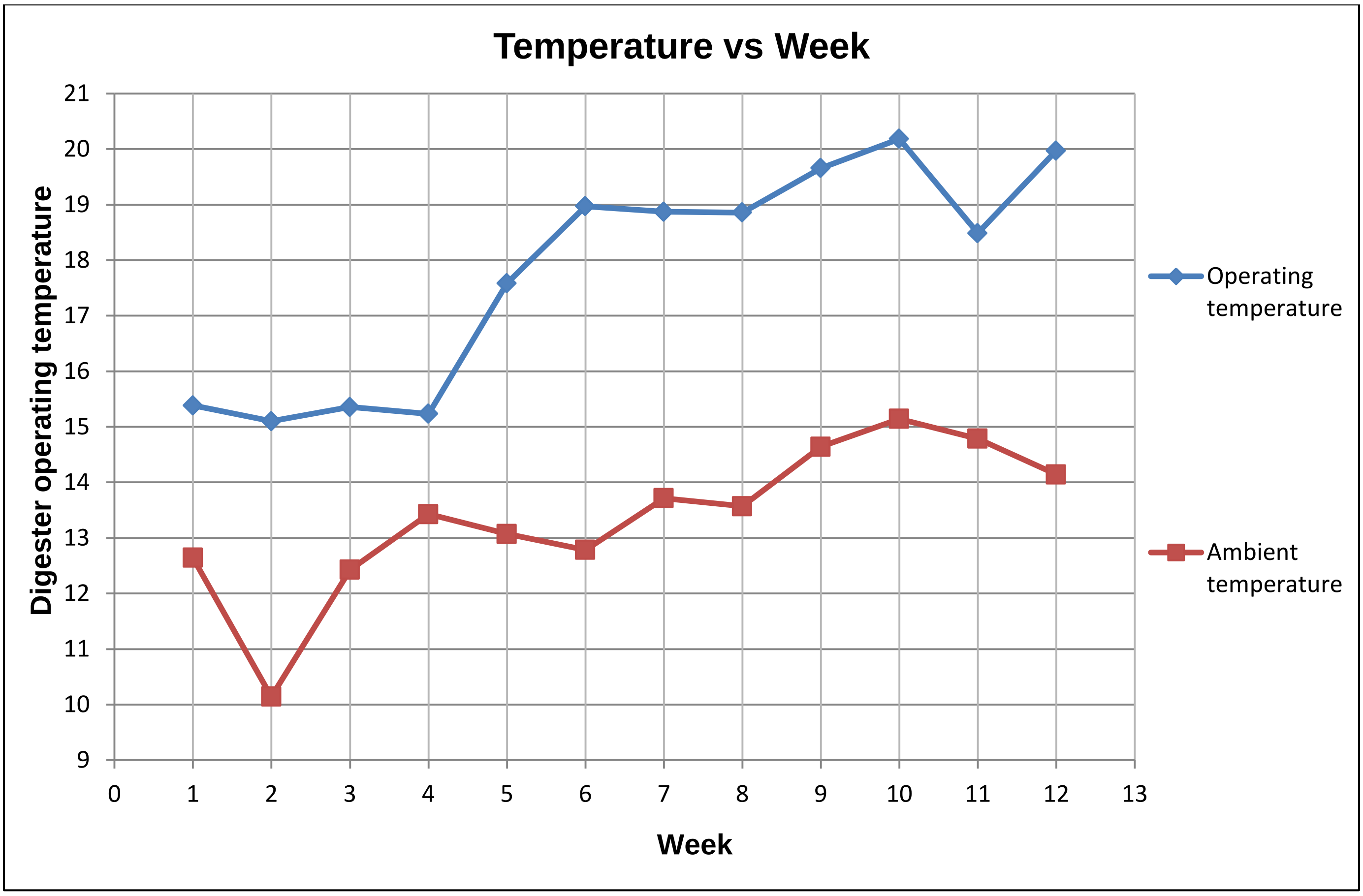


Figure 4-9: Operating and Ambient temperature during cold and warm water operation

During weeks 7 and 8 the digester was loaded daily with 500 ℓ of warm waste water per day, however the operating temperature remained constant at 18.9 °C. The operating temperature is similar to week 6 which was only loaded with 400 ℓ per day of warm waste water. This could be due to additional thermal loading also leading to increased heat losses before reaching the thermocouple at the discharge of the digester.

During weeks 9 and 10 the digester was loaded with 600 ℓ per day of warm waste water. Figure 4-9 also shows the increase in average operating temperature of the digester to 19.7 °C during week 9 and 20.2 °C during week 10. Week 10 represented the highest average operating temperature for the warm water operating period which is 4.9 °C higher than the average operating temperature of the cold water operation.

Week 11 shows the decrease in operating temperature of the digester without warm water loading, a decrease of 1.7 °C on average for the week. Week 12 was again loaded with 600 ℓ per day of warm waste water and the average digester temperature increased 1.5 °C to 20 °C.

During the cold water operation the average difference between operating and ambient temperature was 3.1 °C. During the warm water operation the weekly average difference between operating and ambient temperature, when hydraulic loading took place, ranged between 4.53 °C and 5.86 °C. The warm water operation thus increased the temperature difference between the operating and ambient temperature by between 1.43 °C and 2.76 °C, relative to the cold water operation.

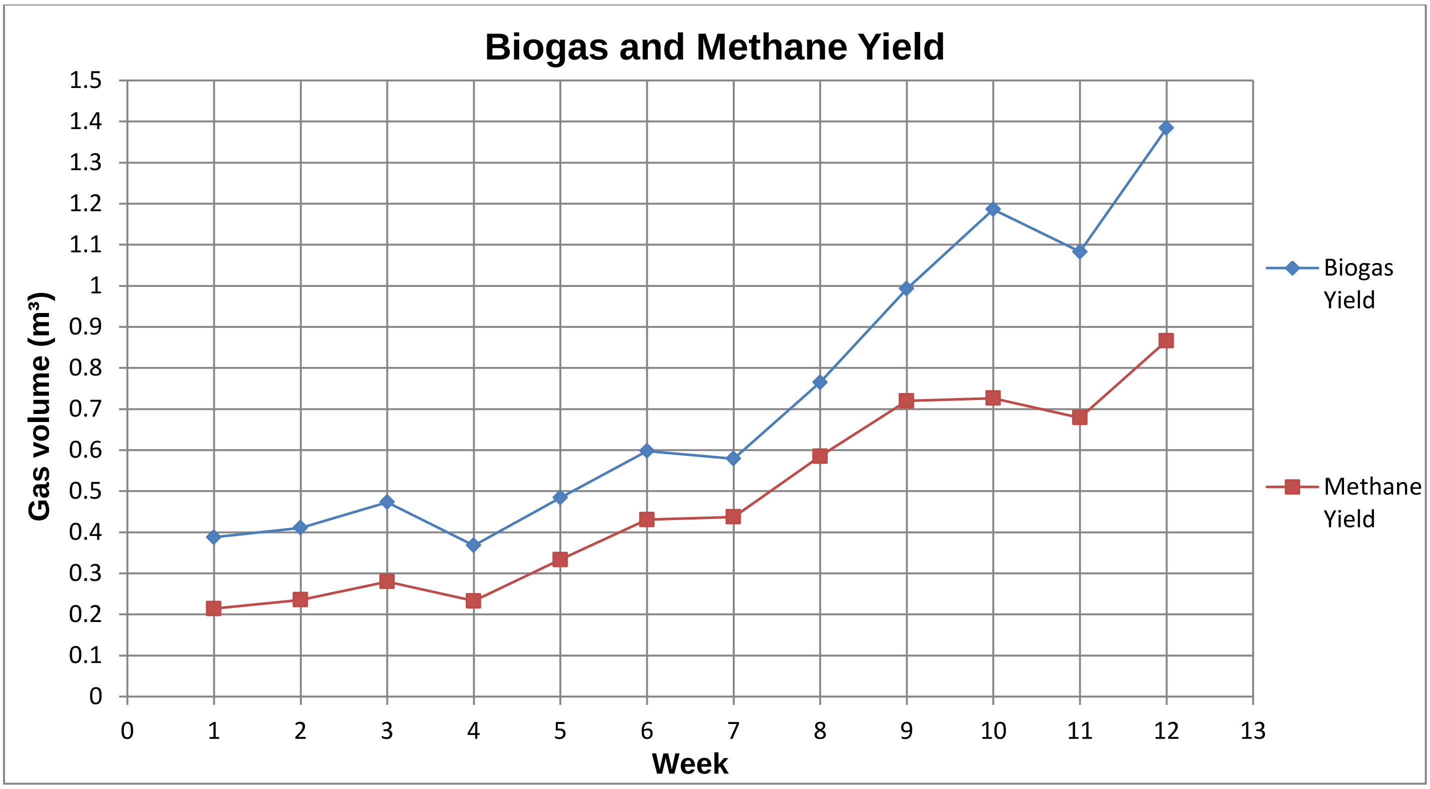


Figure 4-10: Biogas and methane yield

Figure 4-10 shows the total biogas and methane yield for each week of operation. The performance of the anaerobic digester increases with biogas and methane yield as the operating temperature increases. In the final week of warm water operation the biogas and methane yield had increased by 238 % and 260 % respectively, relative to the first 4 weeks of cold water operation. In the final week of warm water operation the average digester operating temperature was 4.7 °C higher than during the first 4 weeks of cold water operation.

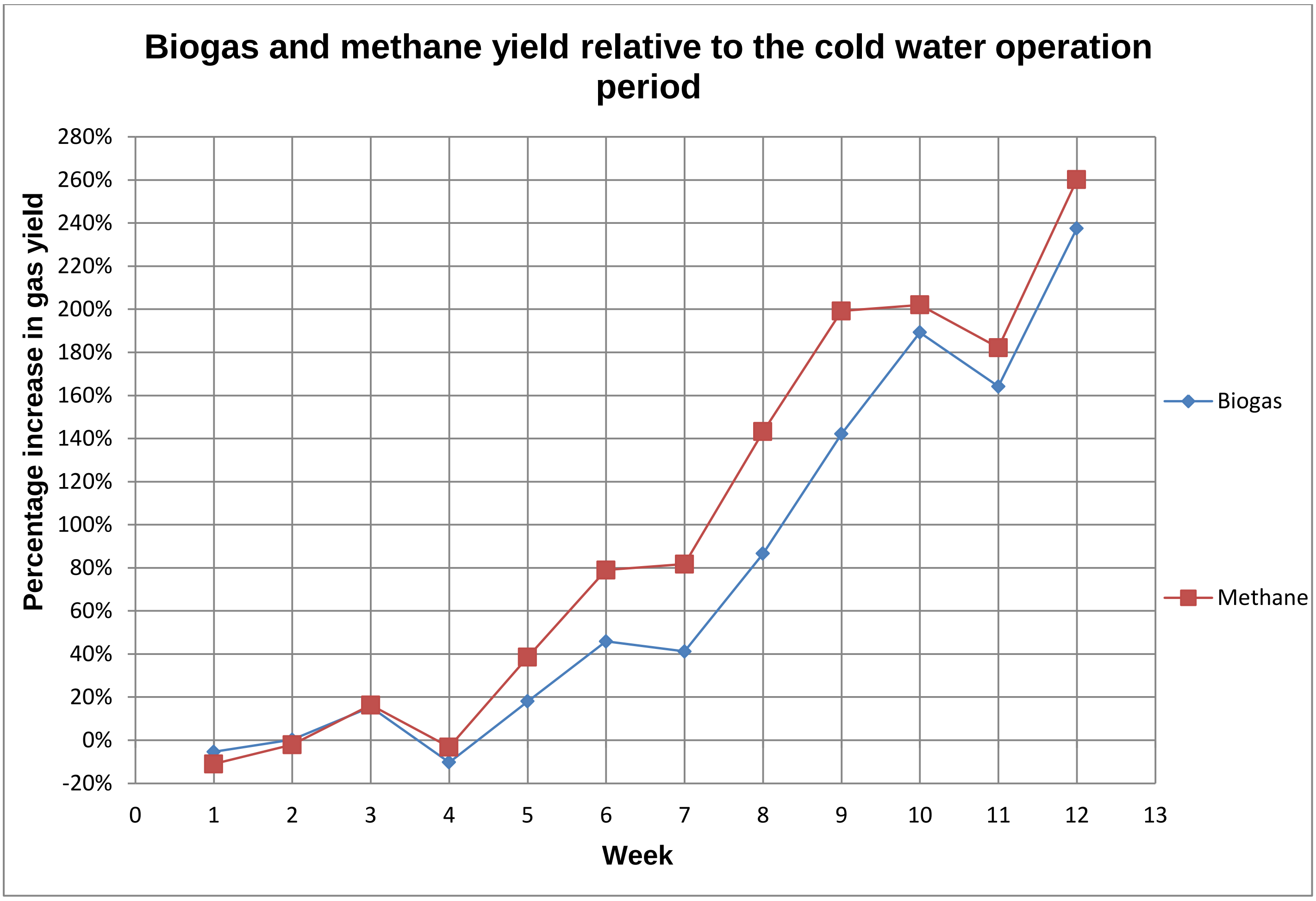


Figure 4-11: Biogas and methane yield relative to operating period

Figure 4-11 shows the increase in performance of the digester relative to the average yield during the cold water operation period. Analysing Figures 4-9, 4-10 and 4-11 the link between average operating temperature and digester performance is clear.

During weeks 1 to 4 the production of biogas and methane deviate by a maximum of 15 % and 16 % relative to the average over the 4 weeks of cold water operation.

During week 1 the digester has the lowest performance relative to the average cold water operating period of - 5 % and - 11 % for biogas and methane respectively. The average operating temperature during this week was 15.4 °C.

The performance of the anaerobic digester during week 2 was 0 % and – 2 % relative to the average cold water operating period for biogas and methane respectively, even though the average operating temperature was 0.3 °C lower than week 1.

The performance of the anaerobic digester during week 3 was 15 % and 16 % higher relative to the average cold water operating period for biogas and methane respectively. The average operating temperature was 15.4 °C, the same as week 1.

The performance of the anaerobic digester during week 4 was - 10 % and - 3 % relative to the average cold water operating period for biogas and methane respectively. The average operating temperature was 15.2 °C, which was the average operating temperature during the cold water operating period.

The average operating temperature during week 5, which is the first week of warm waste water loading, was 17.6 °C. This is 2.4 °C higher than the average operating temperature during the cold water operating period. The performance of the anaerobic digester during week 5 was 18 % and 39 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 6 was 19 °C, which is 3.8 °C higher than the average operating temperature for the cold water operating period. The performance of the anaerobic digester during week 6 was 46 % and 79 % higher relative to the average cold water operating period for biogas and methane respectively. The continued increase in operating temperature from week 5 to week 6 under the same warm waste water loading volume shows the digester has some thermal reserve from the previous week of warm water loading.

The average operating temperature during week 7 was 18.9 °C, which is 3.7 °C higher than the average operating temperature during the cold water period. The performance of the anaerobic digester during week 7 was 41 % and 82 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 8 was the same as week 7. The performance of the anaerobic digester during week 8 was 87 % and 143 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 9 was 19.7 °C, which is 4.5 °C higher than the average operating temperature during the cold water period. The performance of the anaerobic digester during week 9 was 142 % and 199 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 10 was 20.2 °C, which is 5 °C higher than the average operating temperature during the cold water period. The increase in temperature relative to week 9 again shows the thermal reserve capability of the digester, even though the same volume of warm waste water is loaded into the digester. The performance of the anaerobic digester during week 10 was 189 % and 202 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 11 was 18.5 °C with no hydraulic loading, which is 3.3 °C higher than the average operating temperature during the cold water period. The performance of the anaerobic digester during week 11 was 164 % and 182 % higher relative to the average cold water operating period for biogas and methane respectively.

The average operating temperature during week 12 was 20 °C with no hydraulic loading, which is 4.8 °C higher than the average operating temperature during the cold water period. This again demonstrates the thermal reserve capacity of the digester. The performance of the anaerobic digester during week 12 was 238 % and 260 % higher relative to the average cold water operating period for biogas and methane respectively. Week 12 produced the highest digester performance figures.

The warm waste water hydraulic loading of 500 ℓ per day increased the digester methane production by an average of 112 %, while the average operating temperature was 3.7 °C higher than the cold water operating temperature.

The warm waste water hydraulic loading of 600 ℓ per day increased the methane production by 220 % relative to the cold water operating period, while the average operating temperature was 4.7 °C higher when compared to the cold water operating period.

The increase in biogas production relative to the cold water operation was significant. The maximum average weekly operating temperature increase attained relative to the cold water operation was 4.9 °C. The maximum average weekly methane production was 2.6 times higher than the average methane production during the cold water operation period.

Figures 4-12 and 4-13 show the biogas yield vs average operating temperature and methane yield vs average operating temperature respectively. The figures show that with increasing average operating temperatures both biogas and methane yield increases. The exponential equations represent the trend lines best fitting the data points. The correlation coefficient R^2 indicates that the methane yield data fits the exponential function trend line, closer than the biogas yield data. This can also be observed from Figures 4-12 and 4-13.

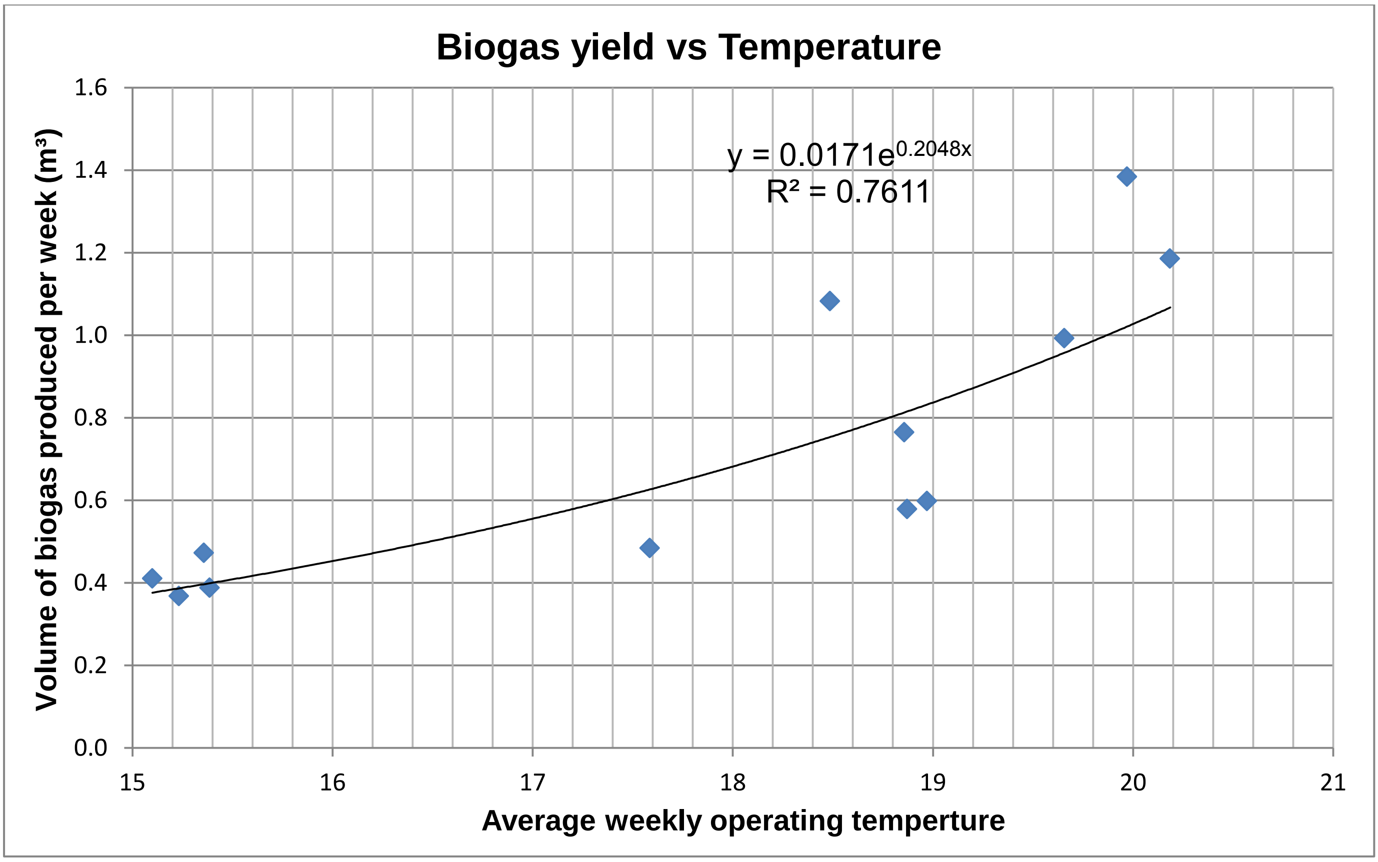


Figure 4-12: Weekly biogas yield vs Average weekly operating temperature

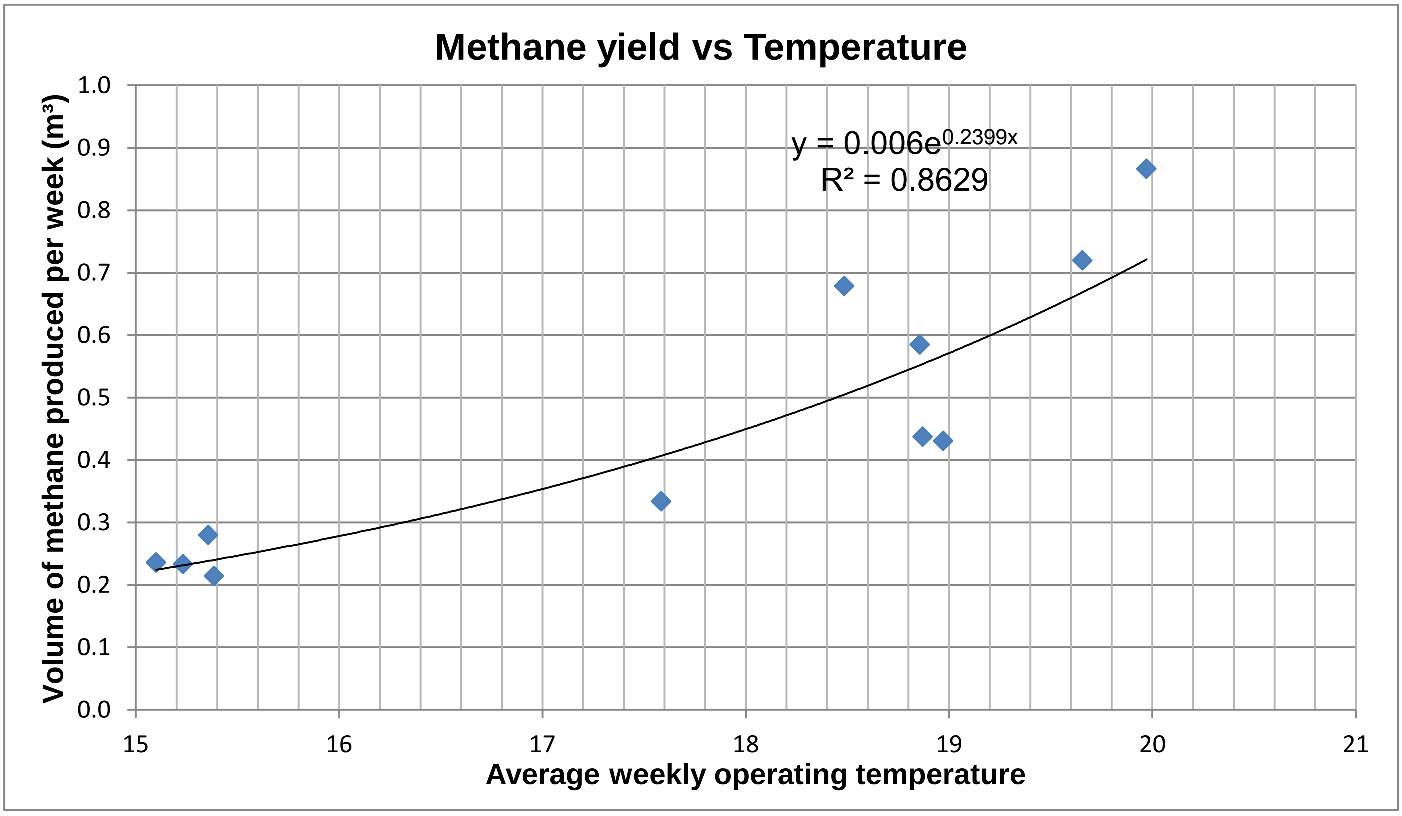


Figure 4-13: Weekly methane yield vs Average weekly operating temperature

4.2.5 The effect of pH on biogas and methane concentration

One observation made during the operation of the digester was the relation between the pH and the composition of biogas produced. The lower the operating pH relative to 7 the lower the methane concentration of biogas produced. The Figure 4-14 shows the relation between operating pH on methane content of biogas produced. The higher the operating pH the higher the methane concentration of biogas produced. However, two distinct clusters of methane composition are seen in the higher of the observed pH ranges (> 6.5), one between 60 and 65%, the other between 69 and 76%.

Based on Figure 4-12 and 4-13 the increase in operating temperature of the LMH anaerobic digester directly affects both the biogas and methane yield. However the increase in methane yield is related to the operating temperature while the biogas produced is affected by both the operating temperature and operating pH.

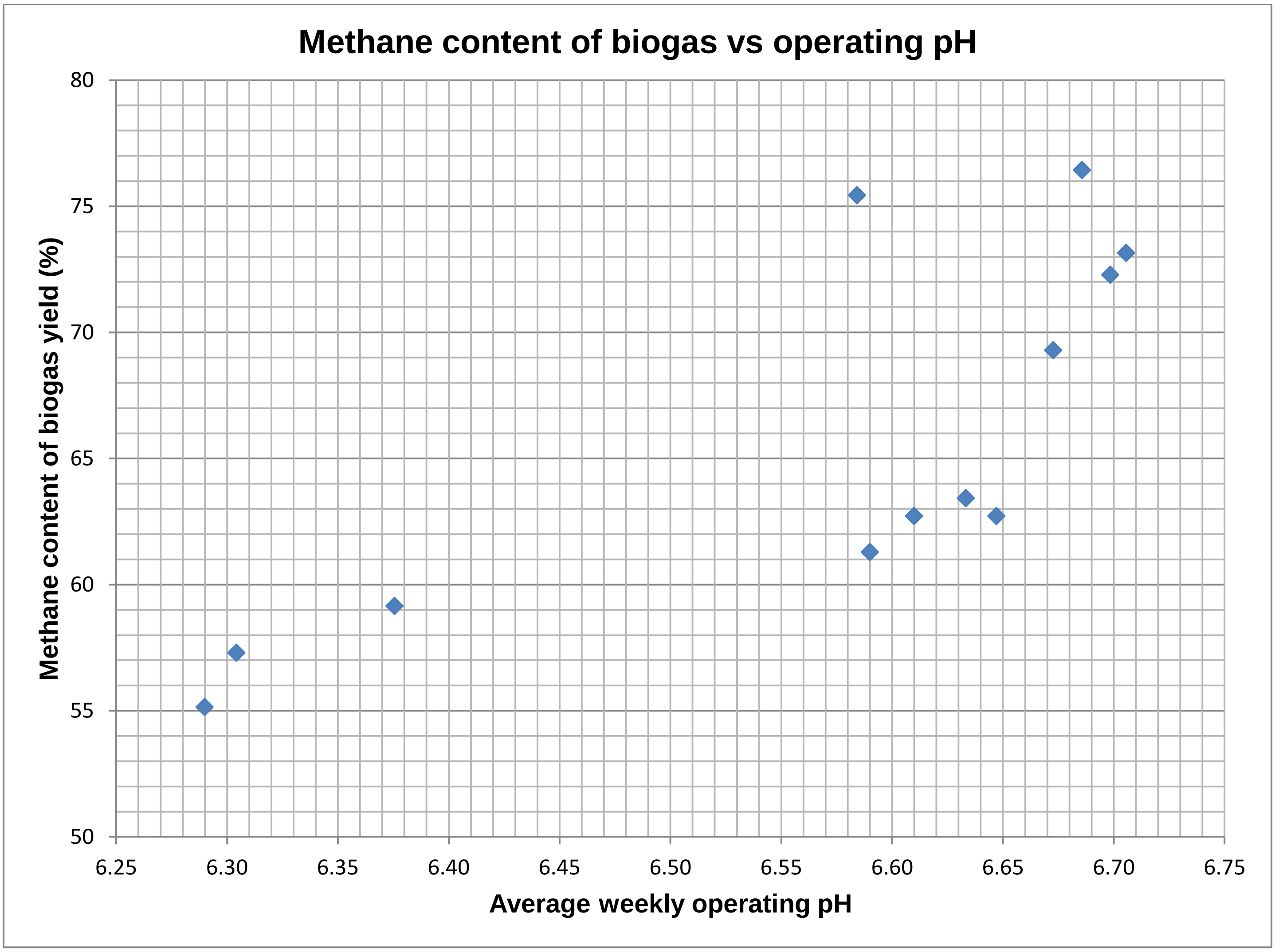


Figure 4-14: Average weekly operating pH vs Percentage methane content of biogas yield

4.2.6 Discussion of key questions related to hypothesis 2

Key question 3 states: What is the average biogas production of the LMH anaerobic digester when operated optimally but without warm water addition?

The average operating temperature of the anaerobic digester during the cold water operation period was 15.3 °C. The average weekly biogas and methane production during the cold water operation was 0.41 m^3 and 0.241 m^3 respectively, with an average methane content of 59 %.

Key question 4 states: Is it technically feasible to use the heat from the LMH waste water pipeline to heat the digester?

Based on the LMH waste water temperature measurements discussed in the first half of this chapter, the morning temperature peak of waste water leaving the LMH residence is about 15 °C higher than the average ambient operating temperature of the LMH anaerobic digester. The waste water outlet drain at the LMH residence was large enough for the installation of a submersible centrifugal pump. It was technically feasible to use the warm water from the LMH waste water pipeline.

Key question 5 states: What is the temperature increase relative to the cold water operating temperature of the LMH residence digester as a result of warm water addition?

The warm waste water hydraulic loading volume of 600 ℓ per day increased the average weekly operating temperature of the LMH anaerobic digester by a maximum of 4.9 °C, which is close to the 5 °C as hypothesised in chapter 3.1. All temperatures measured are at the discharge of the LMH anaerobic digester. The actual average operating temperature during the warm water operation is expected to be slightly higher than the temperature figures measured as the heat losses from inlet to discharge within the digester is not measured. Thus the actual increase in maximum average weekly operating temperature could be slightly above 5 °C during the warm water operation relative to the cold water operation.

Key question 6 states: What is the increase in biogas production as a result of the increased operating temperature of the LMH residence digester and how does it compare to theory?

The increase in average weekly biogas and methane production achieved was 116 % and 148 % respectively, relative to the average weekly cold water operation data. While the maximum increase in average weekly biogas and methane production achieved was 238 % and 260 % respectively, relative to the average weekly cold water operation data.

The theory presented in chapter 2.5.3 states that the increase operating temperature by 10 °C could increase the biogas and methane yield by 100 %. The results achieved showed an increase well above the estimated values from theory.

Hypothesis 2 states: Adding a portion of this over 30 °C water into the LMH digester will result in the digester running at 5 °C above the cold water temperature, and thus increase the productivity of the anaerobic digester.

Hypothesis 2 has been proven as an increase in 4.9 °C was achieved by hydraulic loading of 30 °C warm waste water at a rate of 600 ℓ/day. The performance of the digester was also increased with maximum increases in average weekly biogas and methane production of 238 % and 260 % respectively relative to the cold water operation.

The biogas and methane yield volume per volume of digester is a unit used to compare the performance of different anaerobic digesters. Table 4.7 shows the biogas and methane yield volume per digester volume per day.

Table 4-8: Biogas and methane yield per digester volume per day

	Biogas	Methane
Average cold water operation performance (ℓ/ℓ.d)	0.015	0.009
Average warm water operation performance (ℓ/ℓ.d)	0.032	0.021
Maximum warm water operation performance (ℓ/ℓ.d)	0.049	0.031

The maximum average weekly biogas and methane yield was during the last week of the warm waste water hydraulic loading operation. The biogas and methane yield during this week was 0.049 and 0.031 ℓ of gas produced per ℓ of digester volume per day respectively. The gas was produced at an average operating temperature of 20 °C.

Table 2-2 of Chapter 2 shows the methane and biogas produced in a study by Banks et. al (2010) was 1.48 and 0.93 ℓ of gas produced per ℓ of digester volume per day respectively. This study was for an anaerobic digester using macerated food waste as the feed substrate. The digester was also constantly mixed at an operational temperature of 42 °C, which is 22 °C higher than the maximum temperature obtained in the LMH anaerobic digester. We would thus expect the gas yield per digester volume to be above 4 times higher than that of the maximum gas yield at the LMH anaerobic digester, based on the literature in chapter 2.

The actual comparison of gas yield per volume of digester per day, between the anaerobic digester in the study done by Banks et al. (2010) is 30 and 19 times higher for biogas and methane respectively when compared to the LMH anaerobic digester maximum gas yield.

In the study done by Banks et. al, (2010) the digester was not only operating at 22 °C higher than the LMH anaerobic digester it was also continuously mixed which would also cause an increase in performance. The maceration of the feed substrate would also increase the performance relative to the LMH anaerobic digester. At 42°C the digester in the Banks et al. (2010) study is also operating in the mesophilic temperature range which is the optimum temperature range for biogas production. All of these factors contribute to the actual performance being much higher than the expected performance relative to the LMH anaerobic digester.

The study done by Elango et al. (2006) discussed in Chapter 2 shows the methane and biogas production from an anaerobic digester, operating between 26 to 36 °C using the organic fraction of MSW and domestic sewage and the feed substrate. The methane production rate of this study was 0.0016 to 0.0263 ℓ of gas produced per ℓ of digester volume per day, which is slightly lower than the methane production rates of the LMH anaerobic digester, even though the LMH anaerobic digester was operating at lower temperatures than the digesters in the Elango et al. (2006) study.

These comparisons demonstrate that every anaerobic digestion system is unique and thus shall produce biogas at different rates depending on all the factors mentioned in Chapter 2.4.

5 Conclusions and Recommendations

This dissertation set out to investigate the performance of a 6 m³ anaerobic digester at different operating temperatures using food waste as the feed substrate.

The first objective of this dissertation was to determine the day to day consistency of the temperature profile for the waste water leaving the LMH residence. This was done to determine if it is technically feasible to load the digester with warm waste water, in order to increase the operating temperature of the anaerobic digester, and thus increase its performance. The approach taken was to measure the temperature profile of waste water leaving the LMH residence randomly between the months of February and June 2016.

The second objective of this dissertation is to determine the increase in performance of the LMH residence anaerobic digester as a result of a modified operation using warm waste water for hydraulic loading.

The LMH anaerobic digester control operation was done by hydraulic of cold tap water. The digester operating temperature, biogas yield and methane yield was monitored to determine the control operating performance.

The digester was then operated by hydraulically loading the digester with warm waste water. The increase in operating temperature, biogas yield and methane yield during the modified operation was compared to that of the control operation.

5.1 Conclusions

Hypothesis 1 was concerned with the availability of sufficient quantities of sufficiently warm waste water at a defined time of day. It has been proven only for the morning temperature peak of waste water leaving the LMH residence on weekdays when lectures take place. A defined evening peak in waste water temperature leaving the LMH residence has not been observed. The reason for the morning temperature peak of waste water leaving the LMH residence is due to the fact that majority of lectures for undergraduate students take place at 08:00 am. This set time for the start of lectures ensures most students have to wake up and shower before and during breakfast if they want to make it on time for the 08:00 am lecture. For this reason most students shower between 06:30 am and 07:30 am.

The evening peak in average waste water temperature leaving LMH residence has not been observed as students are not as restricted regarding the time period to shower. The students can shower over a larger period from 05:00 pm till late night. Thus even though students might shower at night, due to the larger time period over which this can occur the average temperature peak is not as high as the mornings.

The average temperature of warm water leaving the LMH residence in the morning period between 06:25 am and 07:20 am on weekdays when lectures take place was calculated from measurements to be 30.5 °C.

The volume warm waste water leaving the LMH residence was not measured. However based on observations and actual quantities of warm waste water pumped from the LMH residence waste water outlet drain to the LMH anaerobic digester, the volume of waste warm waste water leaving the LMH residence between 06:25 am and 07:20 am on weekdays when lectures take place is in excess of 2000 ℓ per day.

Hypothesis 2 was concerned with enhanced gas production when some of the available warm waste water is fed into the digester. Its first component has been proven, with a measured maximum temperature increase of 4.9 °C in the digester, as a result of the warm waste water hydraulic loading. The temperature measured within the LMH anaerobic digester has been measured at the discharge of the digester while the hydraulic loading takes place at the inlet. The actual operating temperature during the warm water operation would be higher than the temperature measured at the discharge of the digester, due to the thermal losses between the inlet and discharge of the digester.

The second component of the second hypothesis was also proven correct. The average operating temperature of the anaerobic digester during the cold water loading operation period was 15.3 °C. The average weekly biogas and methane production during the cold water operation was 0.41 m^3 and 0.214 m^3 respectively, with an average methane content of 59%. During the warm water trial, the average increase in weekly operating temperature obtained due to the warm water loading was 3.9 °C and the average weekly biogas and methane production was measured at 0.884 m^3 and 0.597 m^3. This is an increase in average weekly biogas and methane production of 116 % and 148 % respectively, relative to the average weekly cold water loading operation. Maximum increases of 238 % and 260 % respectively, were observed during one week of the hot water trial.

The increase in biogas and methane yield is higher than expected based on theory. The increase in performance of the digester is expected to be less than 50 % based on an average increase in operating temperature of 3.9 °C.

The higher than expected increase in performance of the LMH residence anaerobic digester as a result of the operating temperature increase could be due to the actual operating temperature being higher than the temperature measured temperature at discharge of the digester due to the thermal losses from inlet to discharge. Another factor causing the increased performance could be the additional organic loading and COD contained in the waste water loaded to the digester however as stated in chapter 4.2.1 the additional COD and organic loading is expected to be relatively low.

5.2 Recommendations

Based on the conclusions of this research, the following recommendations are offered:

5.2.1 For the operation of small-scale biogas digesters:

Small scale anaerobic digesters can generate biogas for heating and cooking on site while at the same time using waste food and sewage as the feed substrate. There are various potential applications for small scale anaerobic digesters where waste food and waste water are generated while heating or cooking are required. University residences, restaurants, hotels and households are a few examples of sites where small scale anaerobic digesters could be implemented.

The operating temperature of small scale anaerobic digesters is a very important factor for the performance of the anaerobic digester. This research shows that increasing the operating temperature of a small scale anaerobic digester by as little as 5 °C could double the performance of the anaerobic digester.

The site location for the installation of small scale anaerobic digesters should be investigated at design stage by taking into consideration the operating temperature. The digester could be installed in close proximity to both an organic waste stream and warm waste water that could affect the feasibility of a particular project installation.

5.2.2 For further research:

In this research, the feed substrate inconsistency and absence of active digester mixing could have reduced the performance of the small scale anaerobic digester used.

The environmental ambient temperature varies over the course of this research. A possible research design could test two identical anaerobic digesters under the same environmental conditions, same feedstock but one of them operated on cold water, the other on warm water.

During this research the digester was organically loaded food waste which at times was large pieces of meat, poultry and vegetables. The particle size of the feed substrate can affect the performance of the anaerobic digester. Further research can be done to compare the performance of small scale anaerobic digesters using normal food waste vs using macerated food waste.

During this research the digester was not actively mixed (although the design of the unit allowed for gentle mixing due to water backflow during gas burn-off): Further research could be done to determine the effect of mixing on the performance of small scale anaerobic digesters.

The volume of warm waste water feed to the digester during this research was limited to 600 ℓ per day, based on recommended hydraulic loading rates from literature to prevent a washout of the bacteria within the digester. The maximum hydraulic loading rate recommended by the digester manufacture is 1000 ℓ per day. However the volume of warm waste water actually leaving the LMH residence is much higher than 2000 ℓ per day, based on physical observations during this research. A coil type heat exchanger could be used to transfer additional thermal energy from the warm waste water to the digester. This system could also be automated to measure the temperature difference between the digester and the warm waste water. If the waste water is measured to be a set number of degrees higher than the digester contents, then waste water could be pumped through the heat exchanger to transfer the thermal energy.

Finally, the strongly improved performance of the digester studied in this experiment could have derived from a combined effect of higher temperature (which was well studied) and additional COD loading in the warm water, which was not studied. A future study could thus be designed to investigate the potential contribution of the latter.

6 Ethical considerations

The University of Cape Town requires that any persons planning to undertake research in the faculty of Engineering and the Built Environment (EBE) completes an “EBE Faculty: assessment of Ethics in Research projects” form. This form has been completed and it has been determined that the project does not have the possibility to harm a third party, use human subjects as data sources, involve participation of or provision of services to communities.

This research project is experimental and engineering design orientated.

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zakiya Chikte (**Zakiya.chikte@uct.ac.za**); New EBE Building, Ph 021 650 5739).

Please note – It is important to keep a signed copy of this form as students must include a copy of the completed form with the dissertation/thesis when it is submitted for examination.

Name of Principal Researcher/Student: SANCHEZ CAROLISSEN **Department:** MEC ENG (ERC)

If a Student: **Degree:** MSc SUSTAINABLE ENERGY ENGINEERING **Supervisor:**

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: SMALL SCALE ANAEROBIC DIGESTION OF FOOD WASTE USING SEWAGE WASTE HEAT (PROVISIONAL)

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	[✓ NO]
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	[✓ NO]
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	[✓ NO]
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	[✓ NO]

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	SANCHEZ CAROLISSEN	26/01/2016

This application is approved by:

Supervisor (if applicable):	Alison Hughes	27/01/2016
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	ACTING HOD BRUNO MERVEN	16/9/2016
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		

7 References

Accuweather. 2017. Available: http://www.accuweather.com/en/za/cape-town [2017, January 9]

BiogasPro Agama. 2017. Available: http://www.biogaspro.com/assets/product_information/biogaspro_product_datasheet.pdf [2017, January 10]

Ahring B. K., Ibrahim A.A., and Mladenovska Z., 2001. Effect of temperature increase from 55 to 65 °C on performance and microbial population dynamics of an anaerobic reactor treating cattle manure*. Wat. Res 35(10):2446-2452*.

Amigun. B, von Blottnitz .H, 2010. Capacity-cost and location-cost analysis for biogas plants in Africa, Resources, *Conservation and Recycling 55 (2010) 63-77.*

Angelidaki I, Sanders W., 2004. Assessment of the anaerobic biodegradability of Macro Pollutants. *Rev. Environ. Science and Biotechnol.3:117-129.*

Angelidaki I., Alves M., Bolzonella D., Borzacconi L., Campos., Guwy A. J., Kalyuzhny S., JenicekP., and Lier J. B., 2009. Defining the Biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. *Water. Sci. and Technol59.5: 927-934.*

Archer, D.B., Hilton, M.G., Adams, P. et al. 1986. Hydrogen as a process control index in a pilot scale anaerobic digester. *Biotechnol Lett (1986) 8: 197.* DOI : 10.1007/BF01029380

Banks C.J., and Stentiford E. I., 2007. Biodegradable municipal solid waste*: biotreatment options*. Waste and resource management 160(1):11-18. DOI:10.1680/warm.2007.160.1.11.

Banks C.J, Chesshire M, Heaven S, Arnold R, 2010. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance, *Bioresource Technology 102 (2011) 612–620.*

Bernal MP, Alburquerque JA, Moral R. 2009. Composting of animal manures and chemical criteria for compost maturity assessment: a review. *BioresourTechnol 2009;100:5444e53.*

Boe K, Angelidaki I. 2009. Serial CSTR digester configuration for improving biogas production from manure. *Water Res2009; 43:166e72.*

Brummeler E, Koster IW. 1986. The effect of several pH control chemicals on the dry batch digestion of the organic fraction of municipal solid waste. *ResourConservRecycl1989;3(1):19e32.*

Buffiere P., Loisel D., Bernet N., Delgenes J.P., 2006 Towards new indicators for the prediction of solid waste anaerobic digestion properties. *Water Sci Technol. 53**:**233-240.*

Cheng, Th, Day DL and Steinberg MP, 1978. Methane production from fresh versus dry dairy manure, *Biol Waste 1978, vol 24;297e306.*

Chint meter. 2016. Available: http://www.chintim.com/html/en/index.php?ac=article&at=read&did=485 [2016, January 05]

Cho, J.K., Park, S.C, 1995. Biochemical methane potential and solid state anaerobic digestion of Korean food wastes. *Bioresour. Technol. 52 (3), 245-253.*

Climate maps. Available: http://www.cape-town.climatemps.com/ [2016, August 23]

Coprax. Available: http://www.dpiplastics.co.za/Coprax_PP-R_Hot_and_Cold_Water [2016, January 05]

CSIR, 2013. *Food waste in South Africa – Opportunities and challenges*. Available: http://www.gdard.gpg.gov.za/Services1/Opportunities%20and%20challenges%20of%20food%20waste%20in%20SA%20final.pdf [2016, April 15]

Desai M., Patel V., Madamwar D., 1994. Effect of temperature and retention time on biomethanation of cheese whey-poultry waste-cattle dung. *Environ. Pollut.83:311–315.*

Edenhofer O., Ramon M., and Youba S., 2012. Renewable energy sources and climate change mitigation, *Special report of the intergovernmental panel on climate change*.

Elango D., Pulikesi M., Baskaralingam P., and Sivanesan S., 2006, Production of biogas from municipal solid waste with domestic sewage, dio:10.1016/j.jhazmat.2006.07.003

Energy City. Available: http://www.cityenergy.org.za/uploads/resource_171.pdf [2015, February 2]

Gallert C., and Winter J., 1999. Bacterial metabolism in wastewater treatment systems. *(In: biotechnology) 11a. Weinheim: Wiley VCH.*

Gerardi M. H., 2003. The microbiology of anaerobic digesters. *John Wiley and Sons, INC*

Hartmann H., and Ahring B. K., 2006. Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. *Water science and technology 53(8):7-22.*

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change , Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K*.

Ho, M. 2005. *Biogas bonanza for third world development*. Available: http://www.i-sis.org.uk/BiogasBonanza.php [2016, January 05]

Heo N.H, Park S.C and Kang H, 2006, Effects of mixture ratio and hydraulic retention time on single stage anaerobic co-digestion of food waste and waste activated sludge. Dx.doi.org/10.1081/ESE-120037874.

Jacobs H. E., Haarhoff J., 2004, Structure and data requirements of an end-use model for residential water demand and return flow, *ISSN 0378-4738 = Water SA Vol. 30 No. 3 July 2004*

Kaparaju P., Buendia I., Ellegaard L., and Angelidaki I., 2007. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: Lab scale and pilot scale studies. *Bioresource technology 99: 4919–4928.*

Karim K., Klasson T., Hoffmann R., Drescher S. R., DePaoli D. W., and Al Dahhan M. H., 2005. Anaerobic digestion of animal waste: Effect of mixing. *Bioresource technology .96:1607–1612.*

Kiely G, Tayfur G, Dolan C, Tanji K. 1997. Physical and mathematical modeling of anaerobic digestion of organic wastes. *Water Res 1997;31:34e40.*

Kim J.K, Oh B.R, Chun Y.N, Kim S.W, 2006, Effects of temperature and hydraulic retention time on anaerobic digestion of food waste, *Journal of bioscience and bioengineering, vol, 102, No. 4, 328-332, DOI: 10.1263/jbb.102.328*

Kleinstreuer C, Poweigha T, 1982. Dynamic simulator for anaerobic digestion process. *BiotechnolBioeng1982;24:1941e51.*

Lissens, G., Vandevivere, P., Baere, L., Biey, E. M., and Verstraete W., 2001. Solid waste digesters:process performance and practice for municipal solid waste digestion. *Water science and technology.* 44(8): 99-102.

MaCarthy, P.L and D. P. Smith, 1986. Anaerobic Wastewater Treatment, *Environmental Science and Technology, vol. 20. Pp. 1200-1226*

Mata-Alvarez J., 2002*. Fundamentals of the anaerobic digestion process (In Biomethanization of Organic fraction of municipal solid waste), Amsterdam: IWA publishing company.*

Metcalf and Eddy Inc, 2004. *Waste water engineering treatment and reuse,* fourth edition.

Naik, L., Gebreegziabher, Z., Tumwesige, V., Balana, B., Mwirigi , Austin, G., 2014. Factors determining the stability and productivity of small scale anaerobic digesters, *Biomass and bioenergy 70 (2014) pg 51-57*

Neves L., Gonçalo E., Oliveira R., and Alves M. M., 2008. Influence of composition on the biomethanation potential of restaurant waste at mesophilic temperatures. *Waste management 28: 965-972.*

Prabhudessai V., 2013. Anaerobic digestion of food waste in a horizontal plug flow reactor*, Birla Institute of technology and science Pilani (Rajasthan) India.*

Ralph M., and Dong G.J., 2010. Environmental Microbiology Second. *A John Wiley and Sons, Publication.*

Sheridan C, Petersen J and Rohwer J, 2012, A technical note on modifying the Arrhenius equation to compensate for temperature changes for reactions within biological systems. http://dx.doi.org/10.4314/wsa.v38i1.18

Steffen R., Szolar O., Braun R., 1998, Feedstocks for anaerobic digestion, *Institute of Agrobiotechnology Tulin, University of Agricultural sciences, Vienna.*

Time and date, Available: https://www.timeanddate.com/weather/south-africa/cape-town [2017, January 09]

University of Cape Town. Available: http://www.uct.ac.za/apply/residence/uctresidence/first/residences/ [2016, July 18]

University of Cape Town. Available: https://www.uct.ac.za/usr/shrl/servfac/reslife/T1_Handbook.pdf [2016, July 18]

Vandevivere P., De Baere L., and Verstraete W., 2003. Types of anaerobic digesters for soild wastes *(In: Biomethanization of the organic fraction of Municipal solid wastes. Editor Mata Alvarez). Amesterdam: IWA Publishing Company*

Viswanath P., Sumithra Devi S., and Nand K., 1991. Anaerobic Digestion of Fruit and Vegetable Processing Wastes for Biogas Production. *Bioresource Technology 40:43-48.*

Vlyssides A., Barampouti E.M., and Mai S., 2008. Granulation mechanism of a UASB reactor supplemented with iron. *Anaerobe 14(5):275-279.*

Von Stockar U., Maskow T., Liu J., Marison I.W., and Patino R., 2006. Thermodynamics of microbial growth and metabolism: ananalysis of the current situation. *J. Biotechnol. 121(4):517-533.*

Weather SA. Available: http://www.weathersa.co.za [2017, January 09]

Wong L.T, Mui K.W, Guan Y., 2009, Shower water heat recovery in high-rise residential buildings of Hong Kong, *Applied energy 87 (2010) 70-709*

World weather online, Available: http://www.worldweatheronline.com/cape-town-weather-averages/western-cape/za.aspx [2016, August 23]

Zhang C., Su H., Baeyens J., Tianwei T., 2014, Reviewing the anaerobic digesterion of food waste for biogas production*, Renewable and sustainable energy reviews 38 (2014) 383 - 392*

Zhang R., El-Mashad H. M., Hartman K., Wang F., Liu G., Choate C., Gamble P., 2007. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource technol. 98:929–935.*

Zupancic G. D., and Jemea A., 2010. Anaerobic digestion of tannery waste: semi continuous and anaerobic sequencing batch reactor process. *Bioresource technology. 101: 26-33.*

8 Appendix A: Gas volume meter specification and calibration

The gas volume flow meter details are shown in Figure 8.1 below. The G1.6 Model unit has been installed at the LMH residence kitchen serving the anaerobic digester. The gas volume meter specifications are shown in Table 8.1 below (Chint, 2016). The operating gas pressure of the LMH anaerobic digester throughout the data collection period was always between 0.7 – 5 kPa.

Сертификат

Модель продукта G1.6

Дата экспертизы 08

2010-10

Инспектор

ZHEJIANG FULUKE GAS INSTRUMENT CO.LTD

Figure 8-1: Gas volume meter

Table 8-1: Gas volume flow meter specifications

type technical parameter		**G1.6**	**G2.5**
Qn		1.6 m$^{3/}$/h	2.5 m$^{3/}$/h
Qmax		2.5 m$^{3/}$/h	4m^3/h
Qmin		0.016 m$^{3/}$/h	0.025m^3/h
Cyclic volume		0.9 dm^3	
Operating pressure		0.5-20 KPa	
Total pressure loss		less than 200Pa	
Error	0.1Qmax ≤Q＜Qmax	±1.5%	
	Qmin≤Q≤0.1Qmax	±3%	
Max reading		9999.999 m^3	
Min reading		0.0001 m^3	
Distance between two connection centers (L)		152.4 130 110 90mm	
Connection screw worm(D)		M26x1.5-6g M30x2-6g	

The calibration of the gas meter was checked using 80 ℓ air tight refuse bags. The 80 ℓ refuse bags was used as opposed to 30 ℓ bags due to the favourable cylindrical shape when inflated of the larger 80ℓ bags. The 80ℓ bags when fully filled and sealed were measured to contain 65 ℓ of gas. The gas from the digester was passed through the gas volume meter and collected in the refuse bags. Once the refuse bag was completely filled with gas it was sealed and the dimensions was measured to determine the volume of gas in each bag. Table 8.2 shows the calculated volume based on the bag dimensions, volume recorded by the volume meter, and the calculated error. The maximum calculated error of 3.17% is very close to the 3% error for volumes less than 1.6 m³/h. The calibration of the gas meter was thus still valid.

Table 8-2: Calibration check of gas volume meter

Bag number	Bag volume (ℓ)	meter gas volume (ℓ)	Error (%)
1	65	66	1.52%
2	65	67	2.99%
3	65	65	0.00%
4	65	63	3.17%
5	65	66	1.52%
6	65	67	2.99%
7	65	63	3.17%
8	65	66	1.52%
9	65	65	0.00%
10	65	66	1.52%

9 Appendix B: Pump system design

The pump system design was based on the temperature profile of warm water leaving the LMH residence. The design system duty flow rate was selected at 20 ℓ/min based on the temperature profile and the observation of the flow leaving the LMH residence.

The length of pipe needed was measured on site between the drain containing the waste water and the LMH residence digester. The length of pipe needed between the digester and the drain was measured at 27 meters.

The diameter of the pipeline was selected such that the velocity through the pipe system would be about 1 m/s at the design flow rate. The velocity of 1 m/s minimizes the dynamic head during operation but ensures the velocity is high enough to prevent the setting on solids in the pipeline. The nominal diameter of 20 mm was selected for the 1 m/s velocity at 20 ℓ/min volume flow rate. The resistance calculation for the system curve was based on the Coprax technical manual for 20 mm inside diameter polypropylene pipe and fittings (Coprax, 2016). The total number of fittings installed was two 90° bends and a volume flow meter.

The type of pump-set selected for this application was a submersible pump-set due to the top water level within the drain at 1.5 meters below the ground level. The pump-set selected was a Pedrollo TOP 1 submersible pump-set able to meet the duty point of 20 ℓ/min at 6 m head. Table 9-1 shows the calculated data of the pipe system design.

Table 9-1: Pumped system design data

Volume flow rate (ℓ/min)	Dynamic head due to Pipe (m)	Dynamic head due to volume meter (m)	Flow speed (m/s)	Dynamic head due to bends	Static head (m)	Total System Head (m)	Pump Head (m)
0	0	0	0.00	0.00	0.7	0.70	7
10	0.594	0.1	0.53	0.57	0.7	1.97	
20	1.89	0.2	1.06	2.30	0.7	5.09	6
30	4.32	0.43	1.59	5.16	0.7	10.61	5.6

The pump and system curves are shown in Figure 9-1. The duty point of the pumped system is the intersection of the system curve and pump curve. The duty point as shown in Figure 9-1 is this about 21 ℓ/min.

The actual operating system flow rate was checked when the system was installed and operating. The time taken to fill a 20 ℓ container was measured at 59 seconds. Thus the actual operating duty flow was 20 ℓ/min.

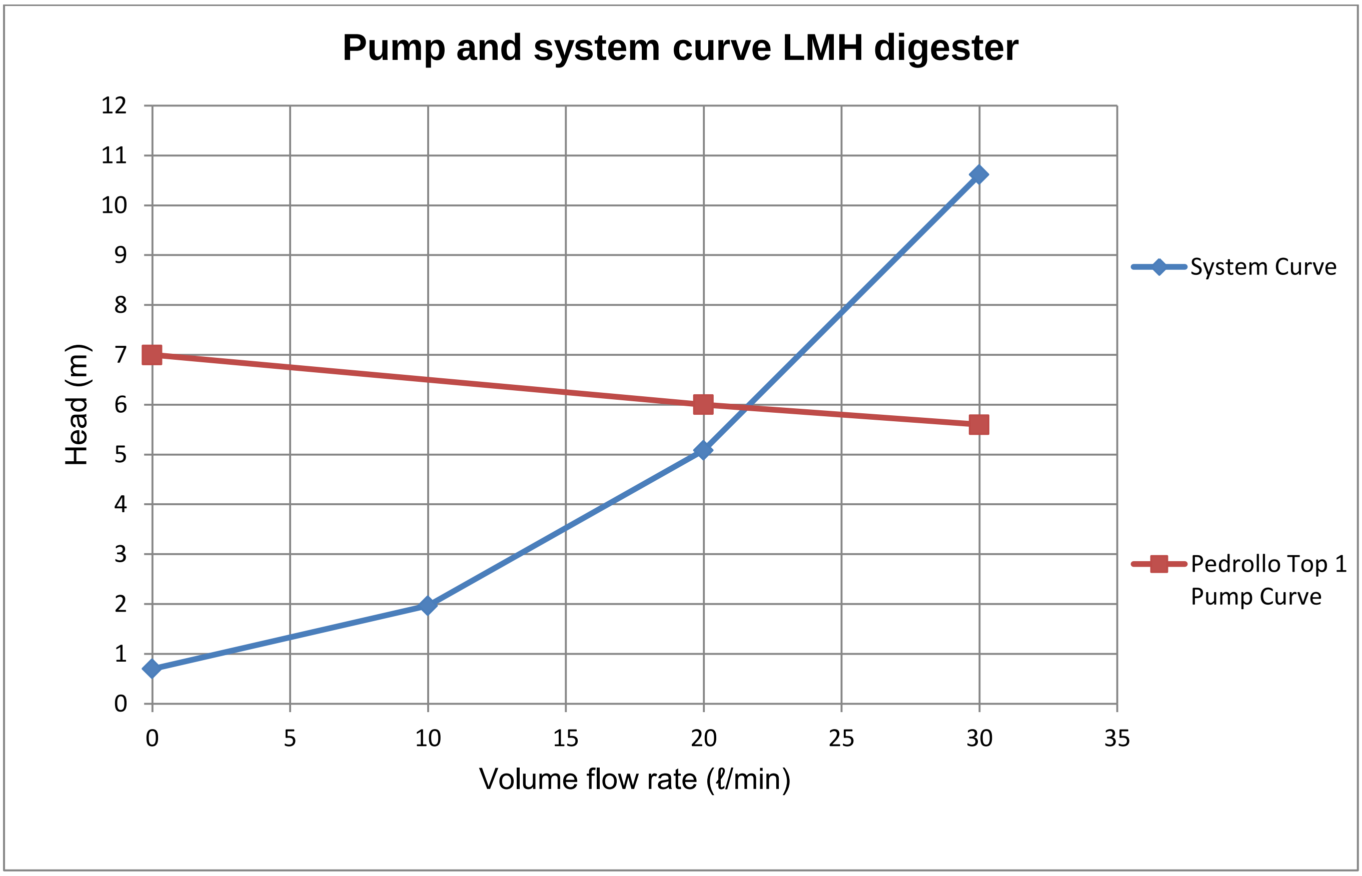


Figure 9-1: Pump and system curve LMH digester

10 Appendix C: LMH residence waste water temperature profiles.

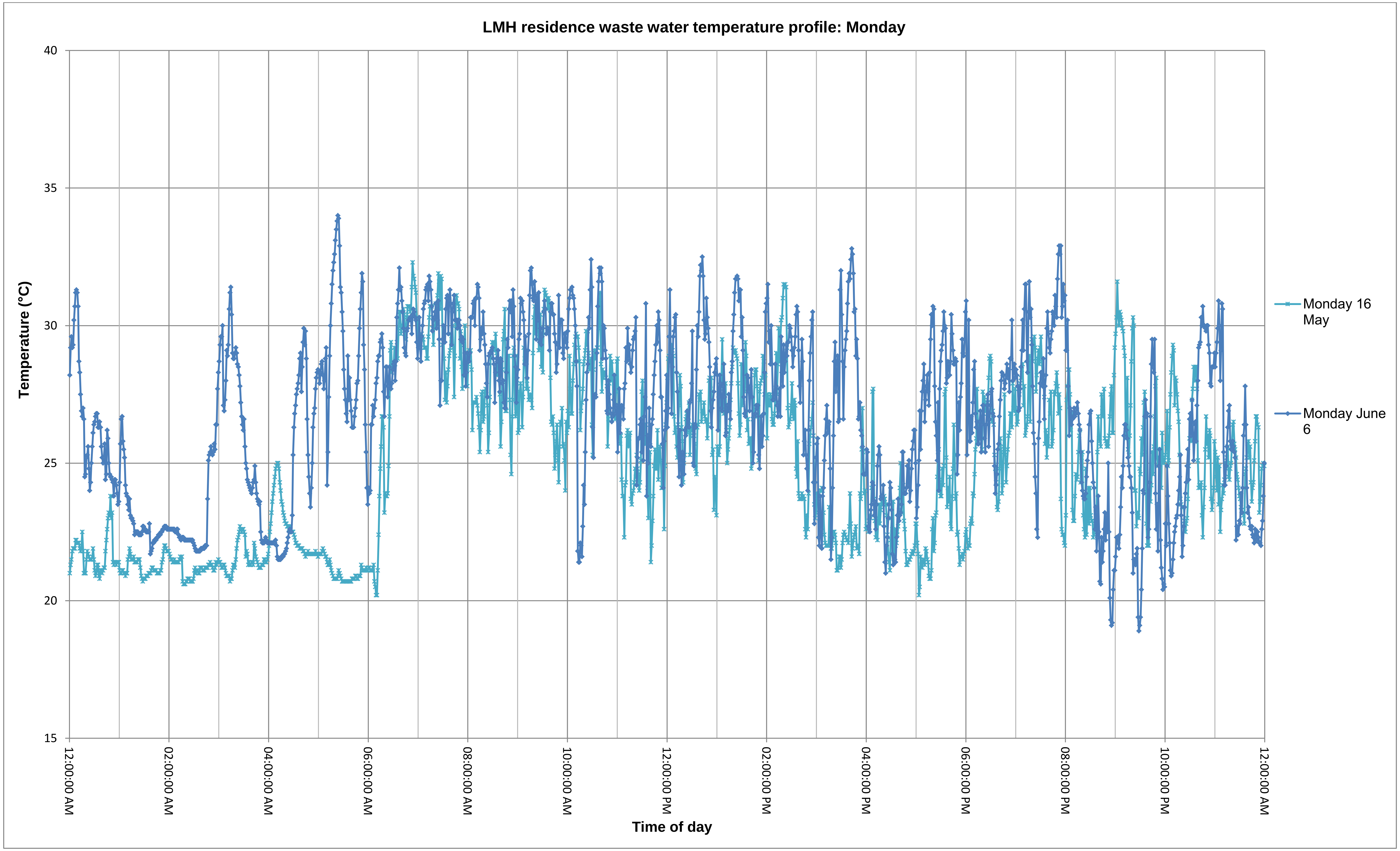


Figure 10-1: LMH residence waste water temperature profile: Monday

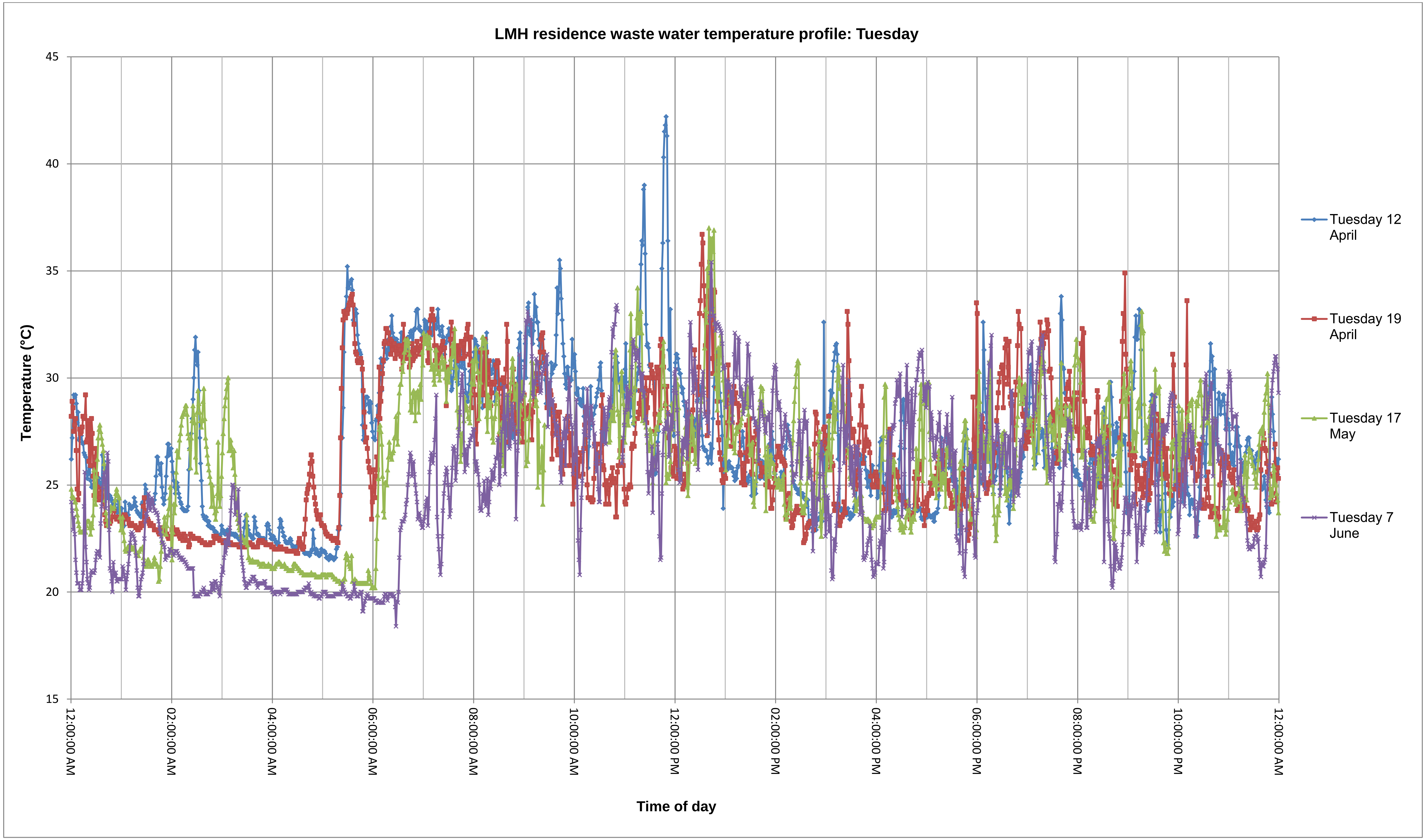


Figure 10-2: LMH residence waste water temperature profile: Tuesday

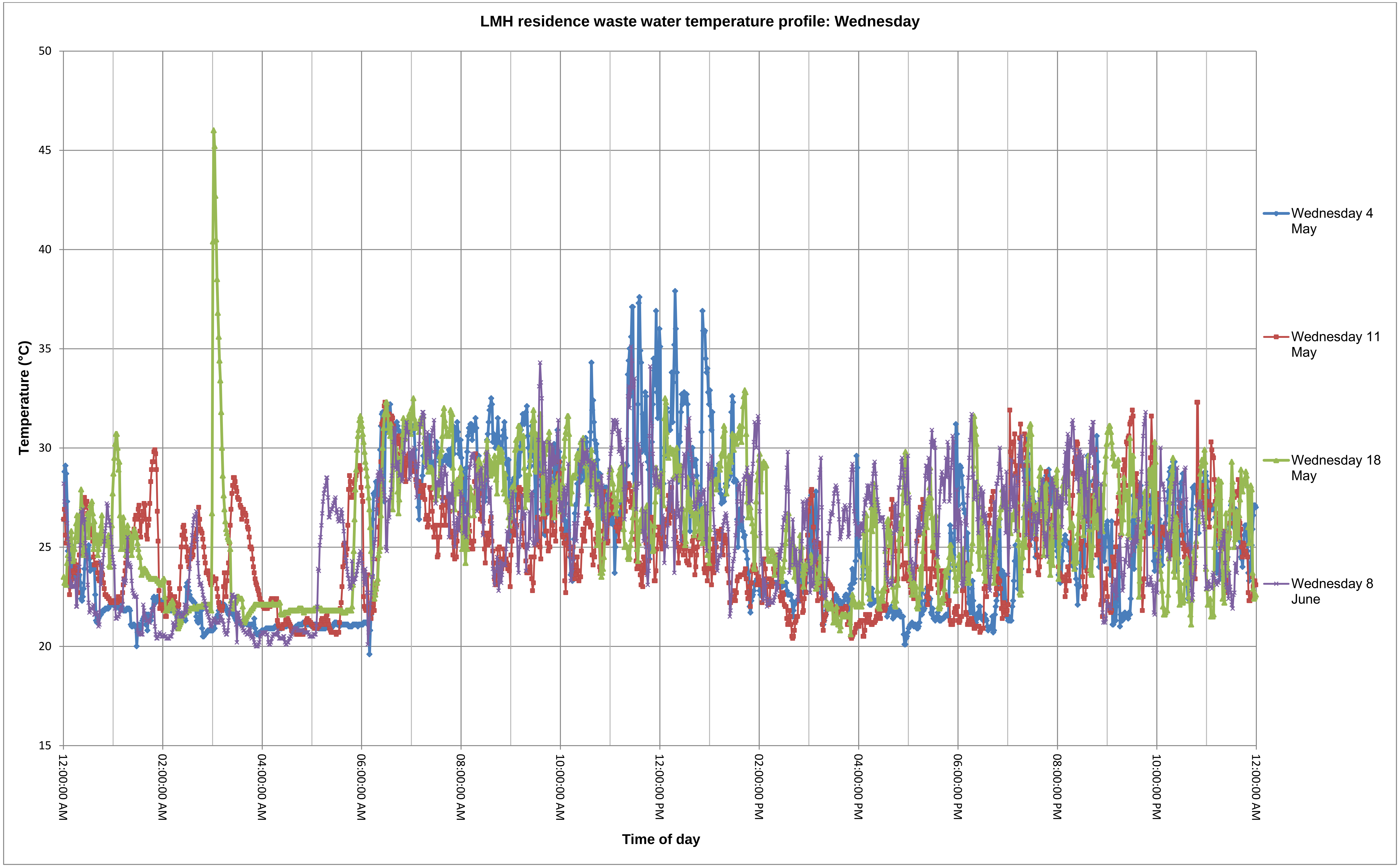


Figure 10-3: LMH residence waste water temperature profile: Wednesday

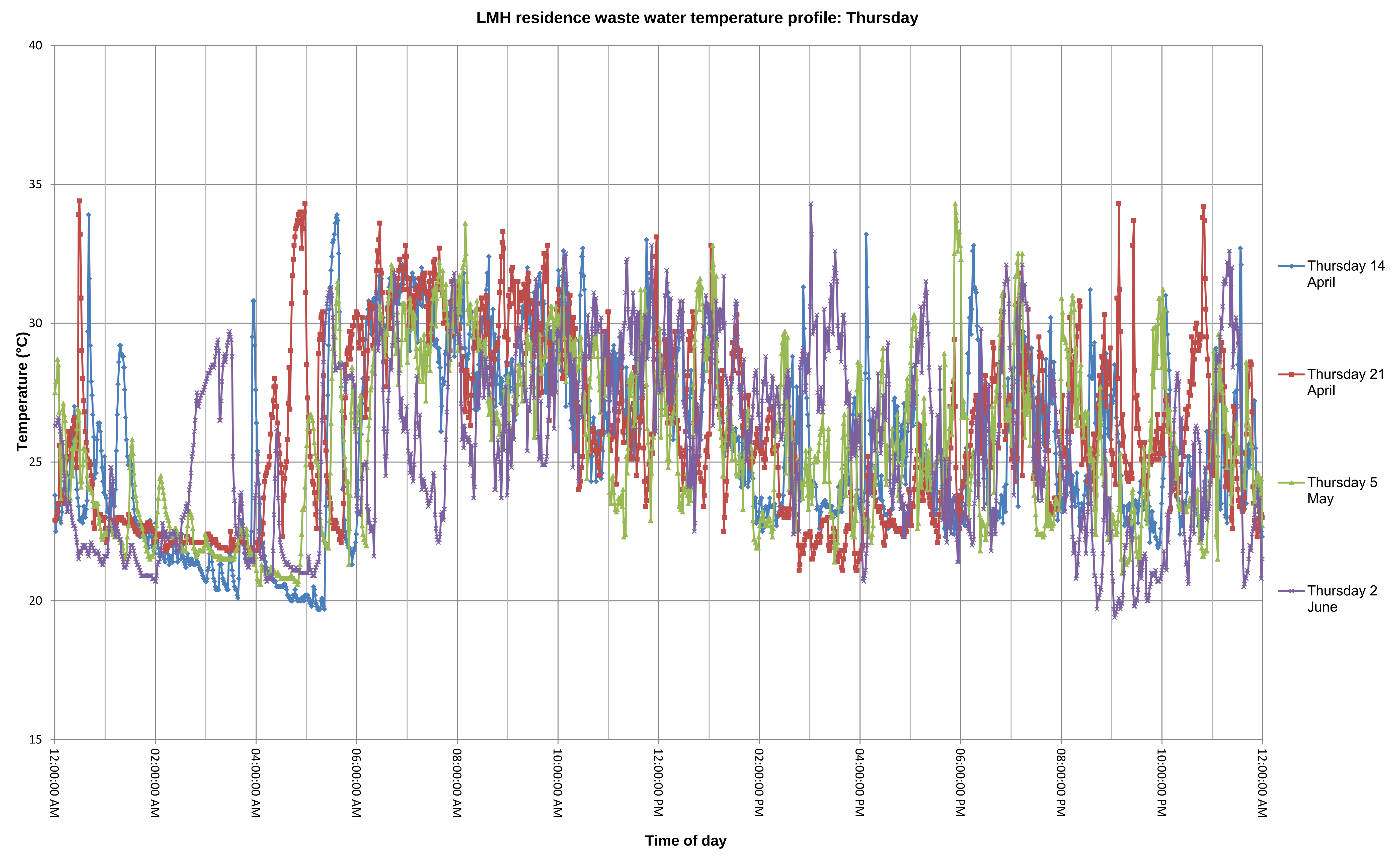


Figure 10-4: LMH residence waste water temperature profile: Thursday

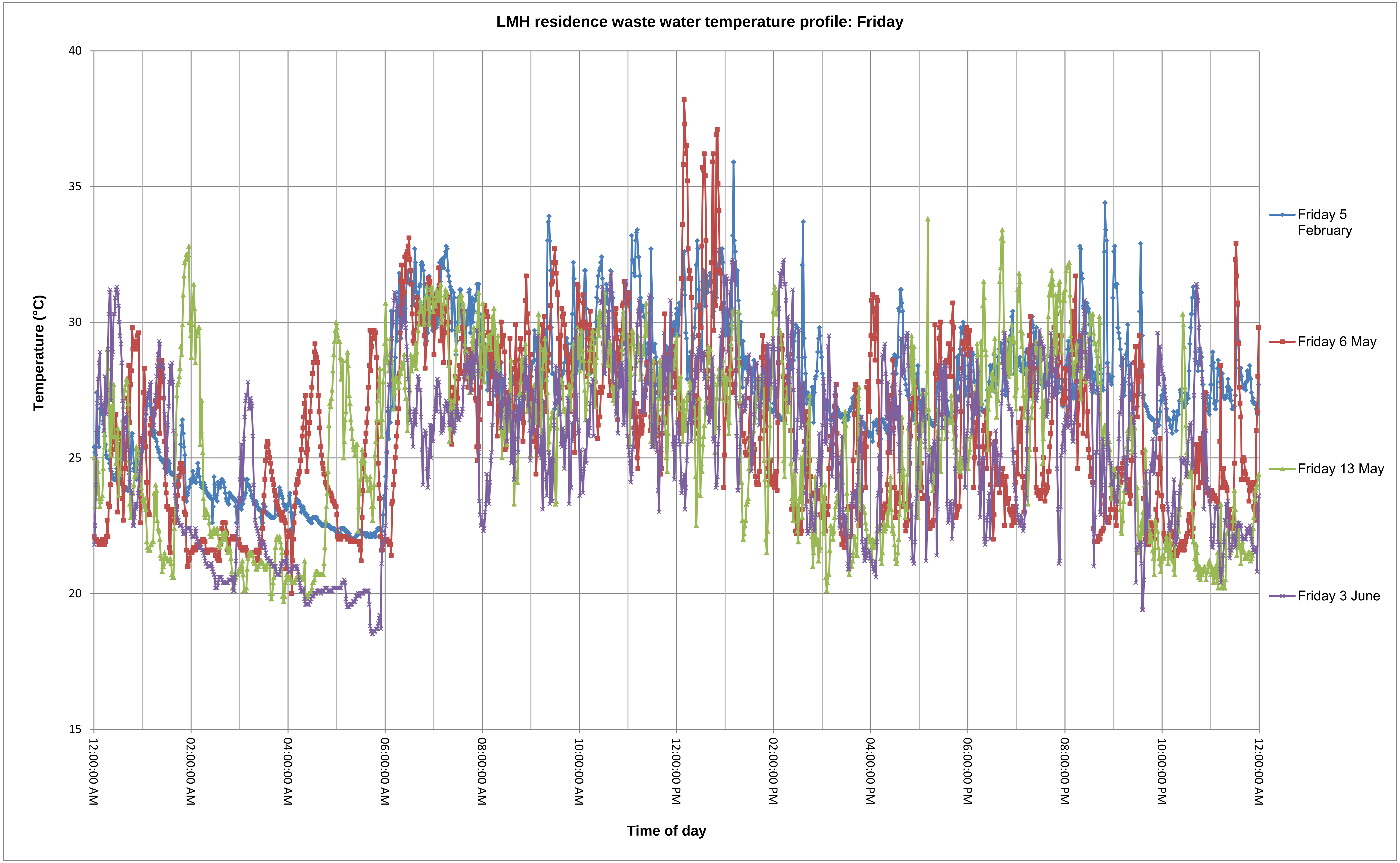


Figure 10-5: LMH residence waste water temperature profile: Friday

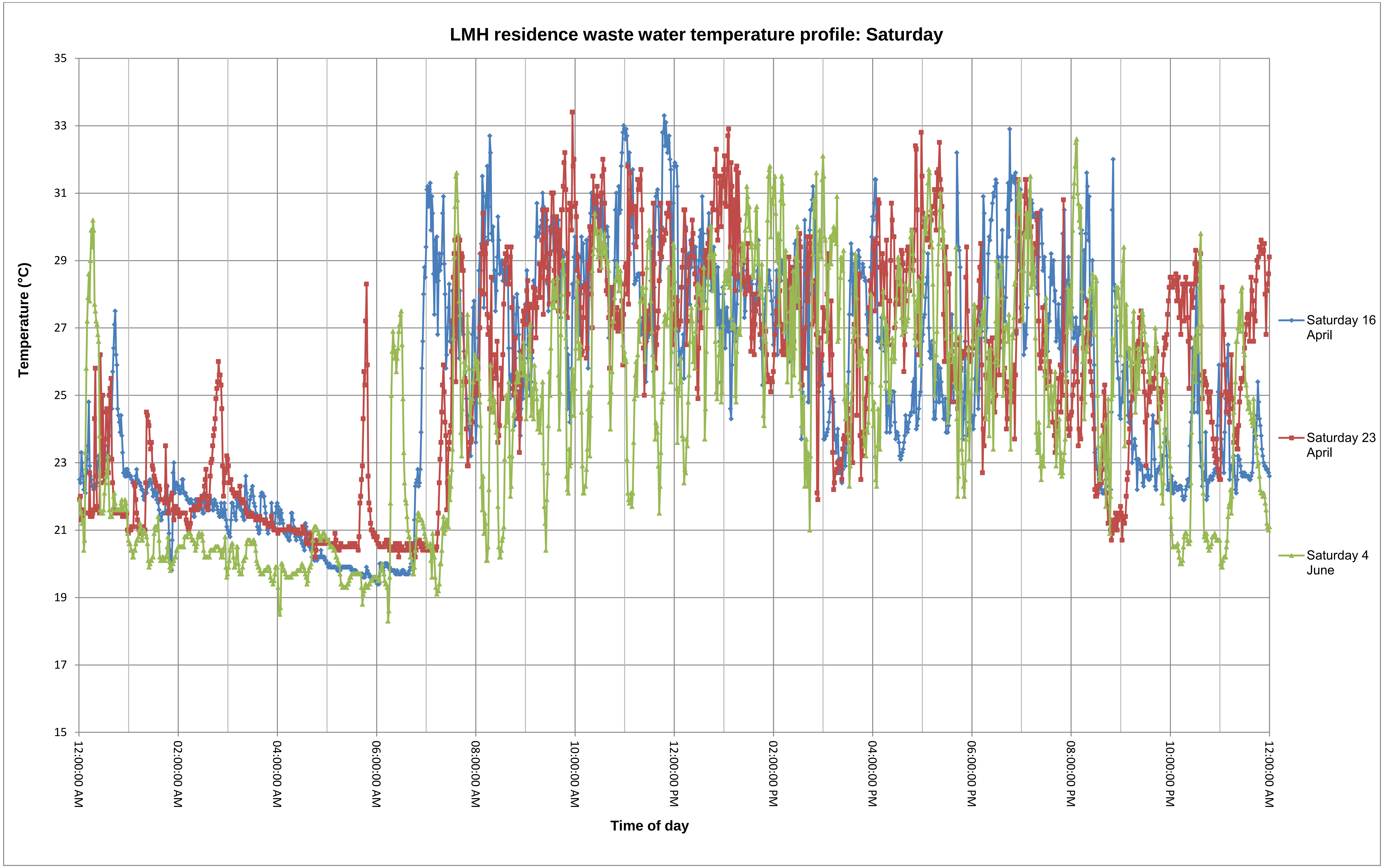


Figure 10-6: LMH residence waste water temperature profile: Saturday

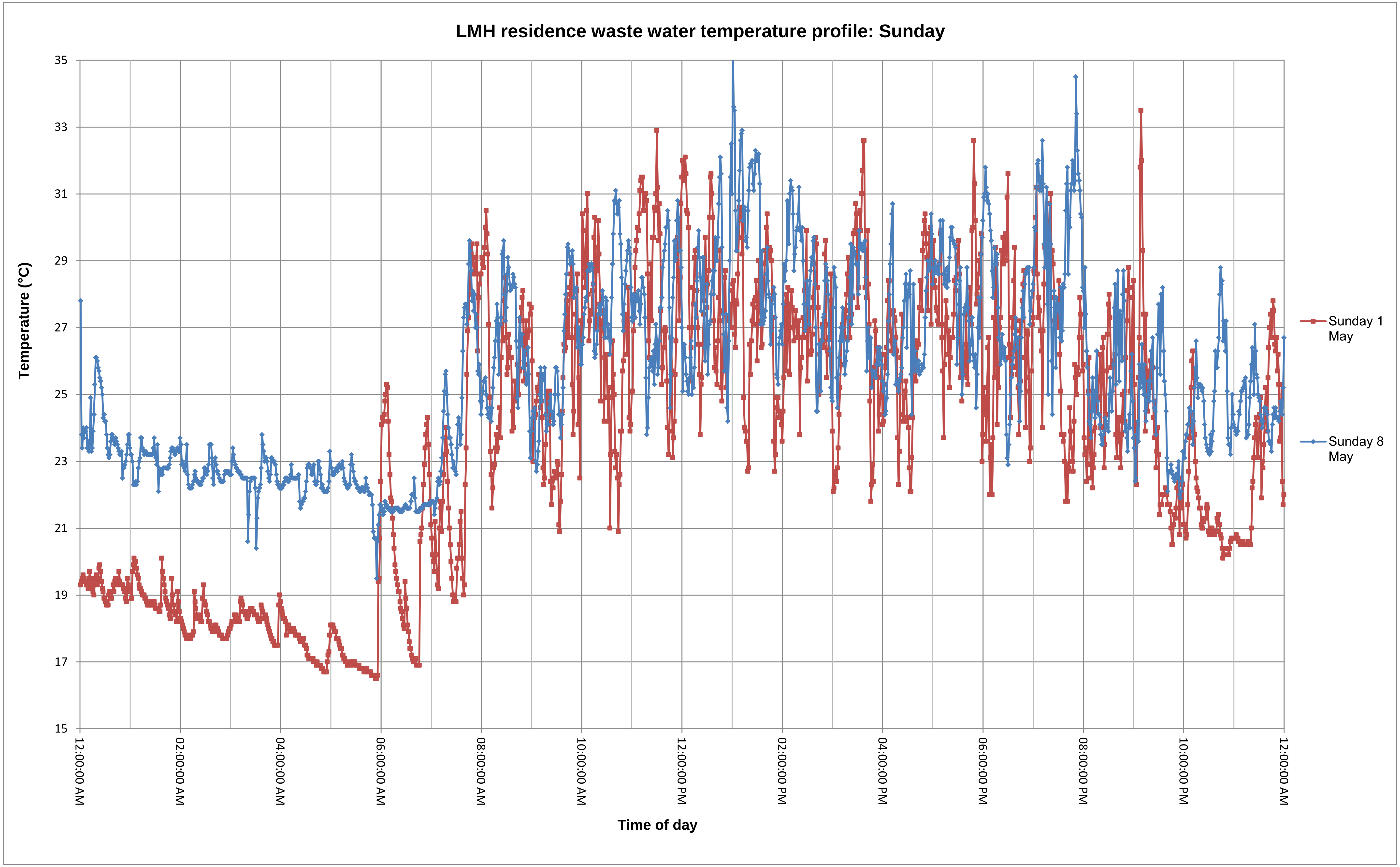


Figure 10-7: LMH residence waste water temperature profile: Sunday

11 Appendix D: LMH anaerobic digester cold water operating temperature profile.

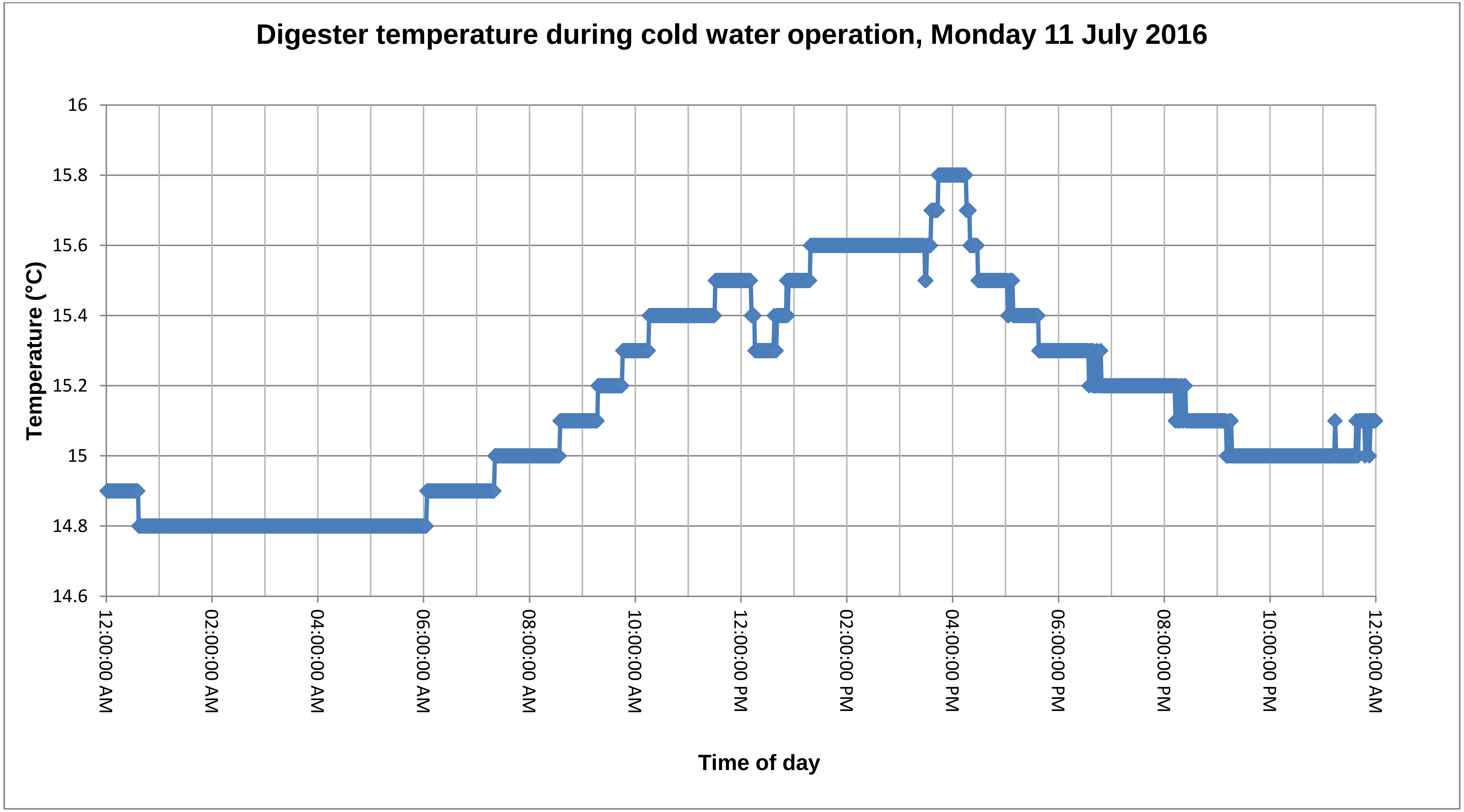


Figure 11-1: Digester temperature during cold water operation, Monday 11 July 2016

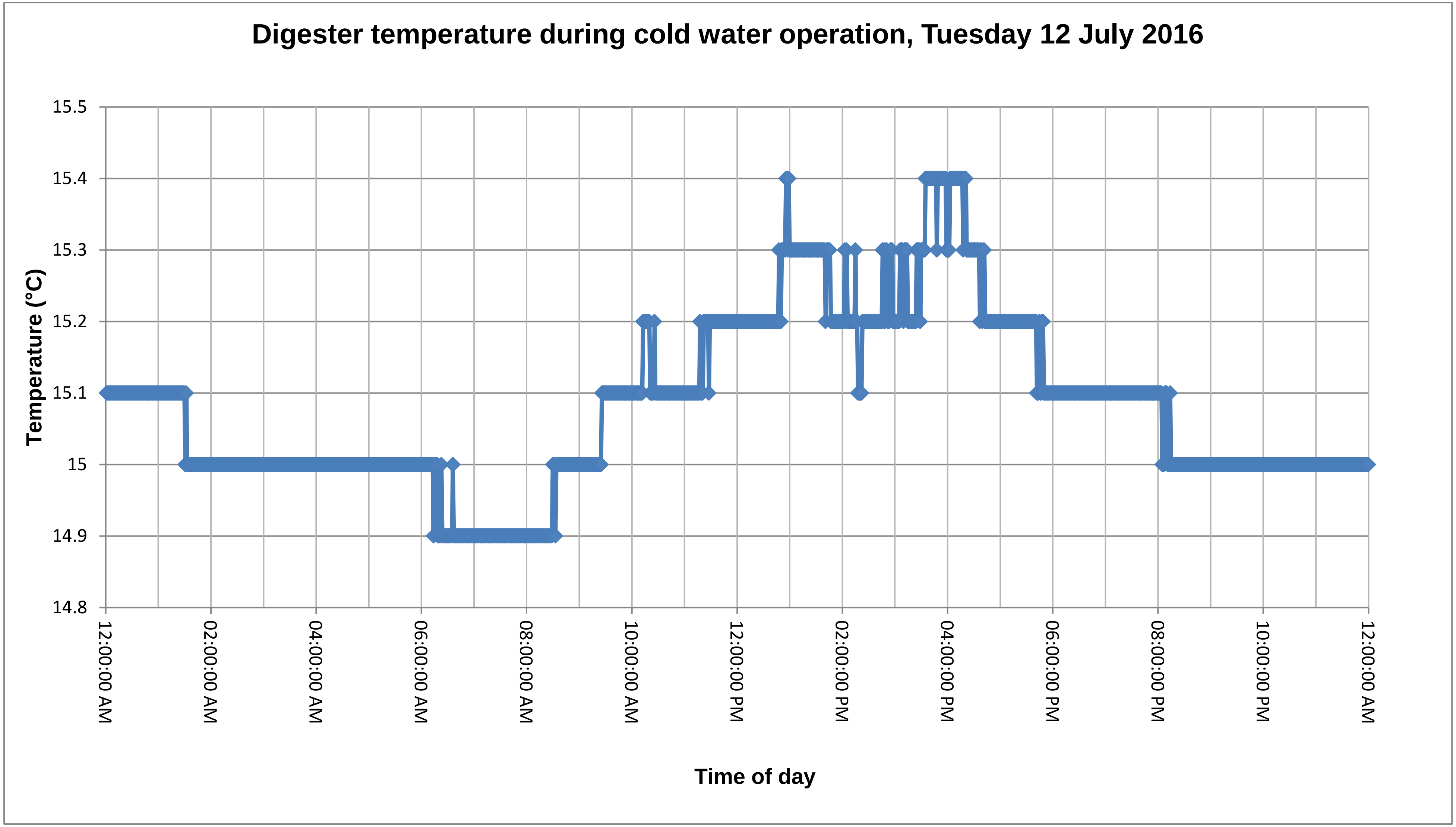


Figure 11-2: Digester temperature during cold water operation, Tuesday 12 July 2016

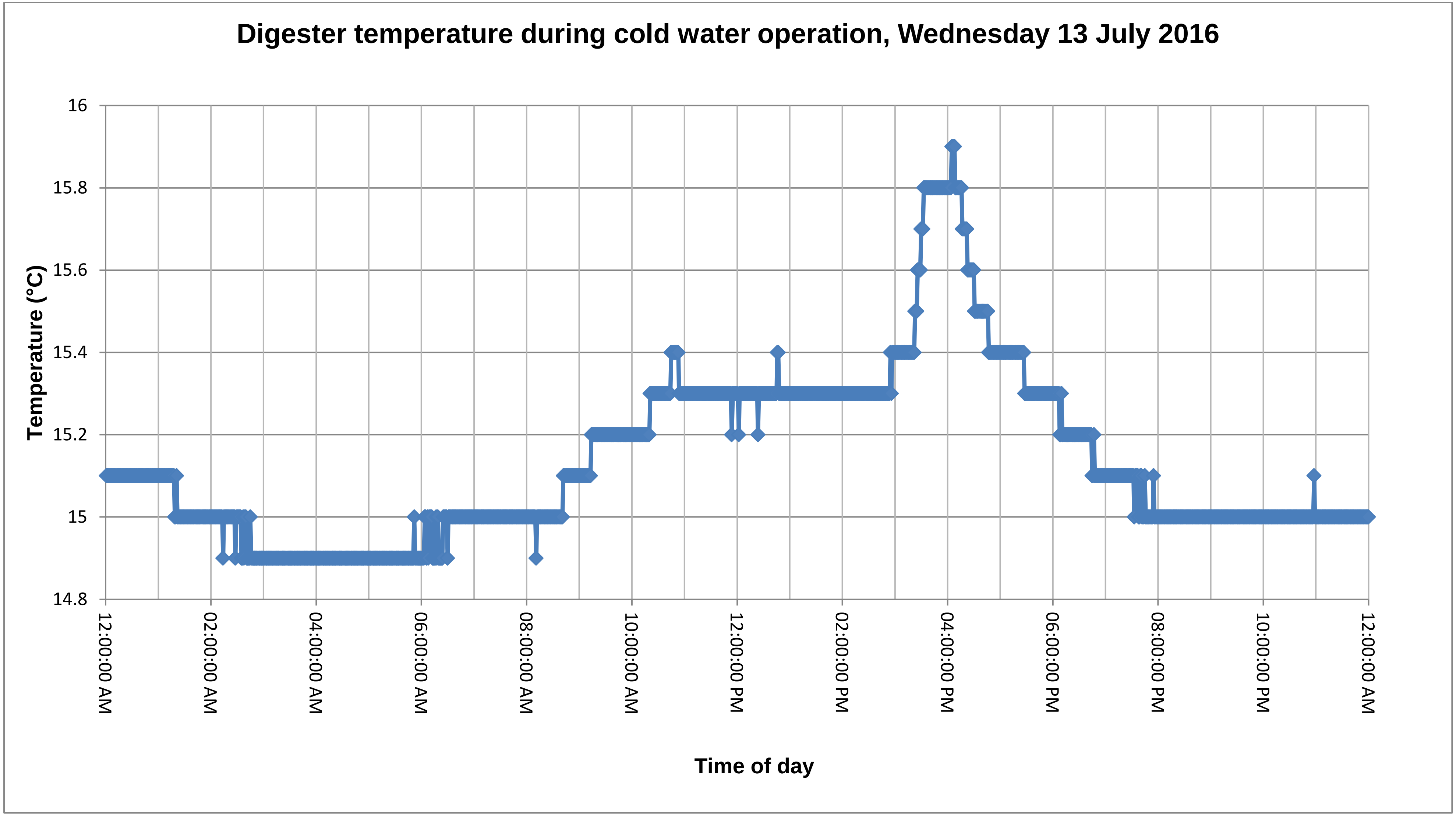


Figure 11-3: Digester temperature during cold water operation, Wednesday 13 July 2016

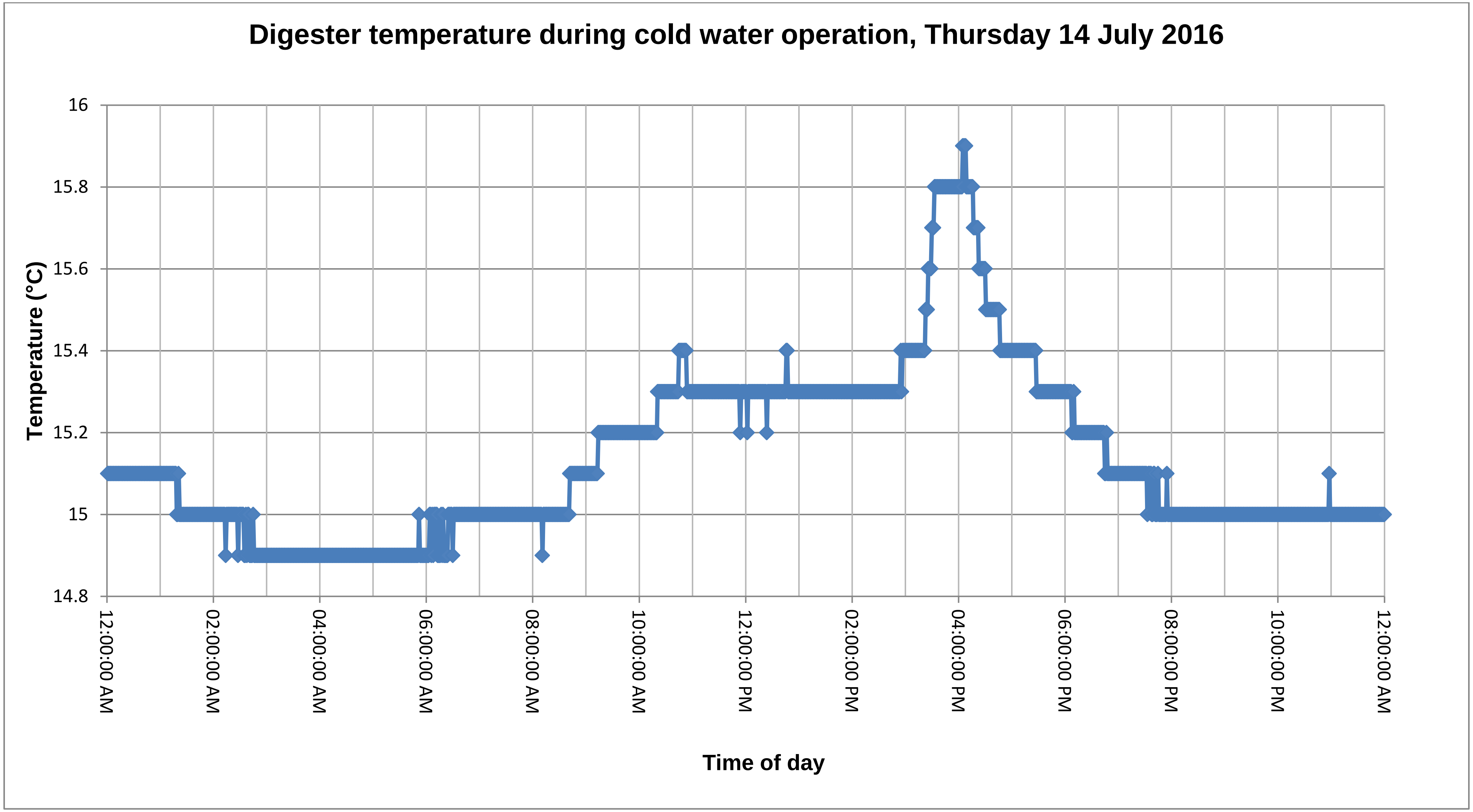


Figure 11-4: Digester temperature during cold water operation, Thursday 14 July 2016

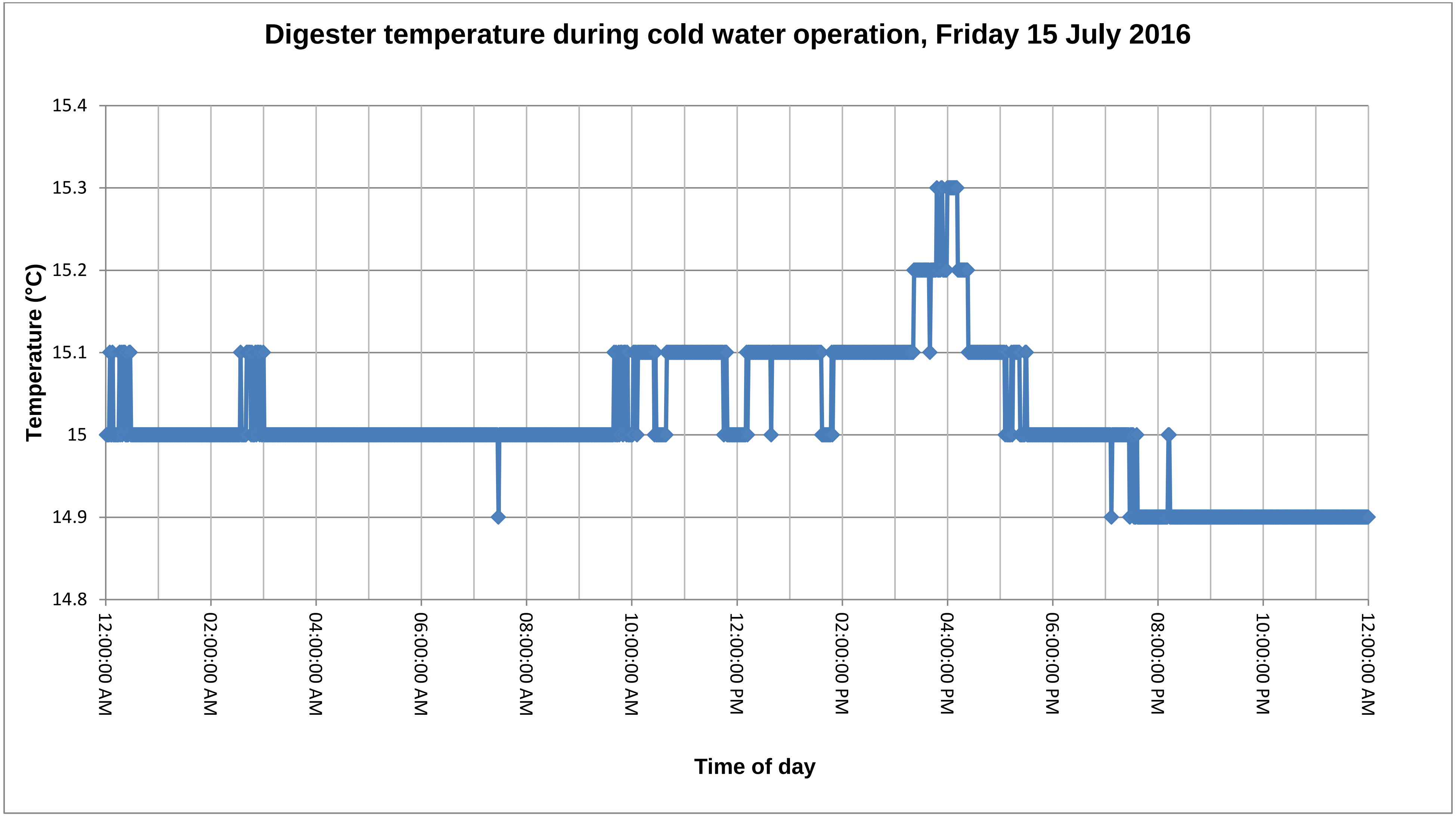


Figure 11-5: Digester temperature during cold water operation, Friday 15 July 2016

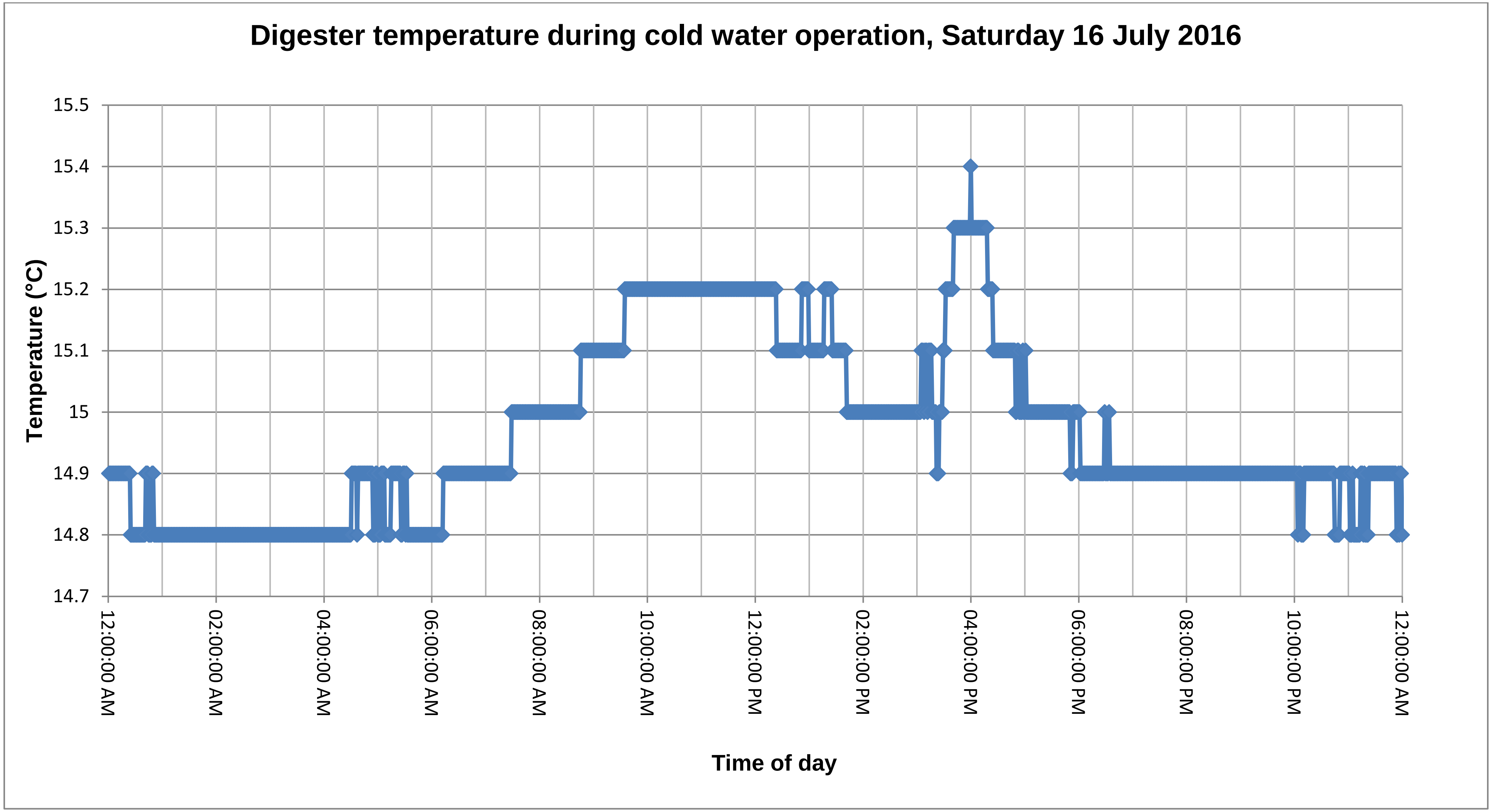


Figure 11-6: Digester temperature during cold water operation, Saturday 16 July 2016

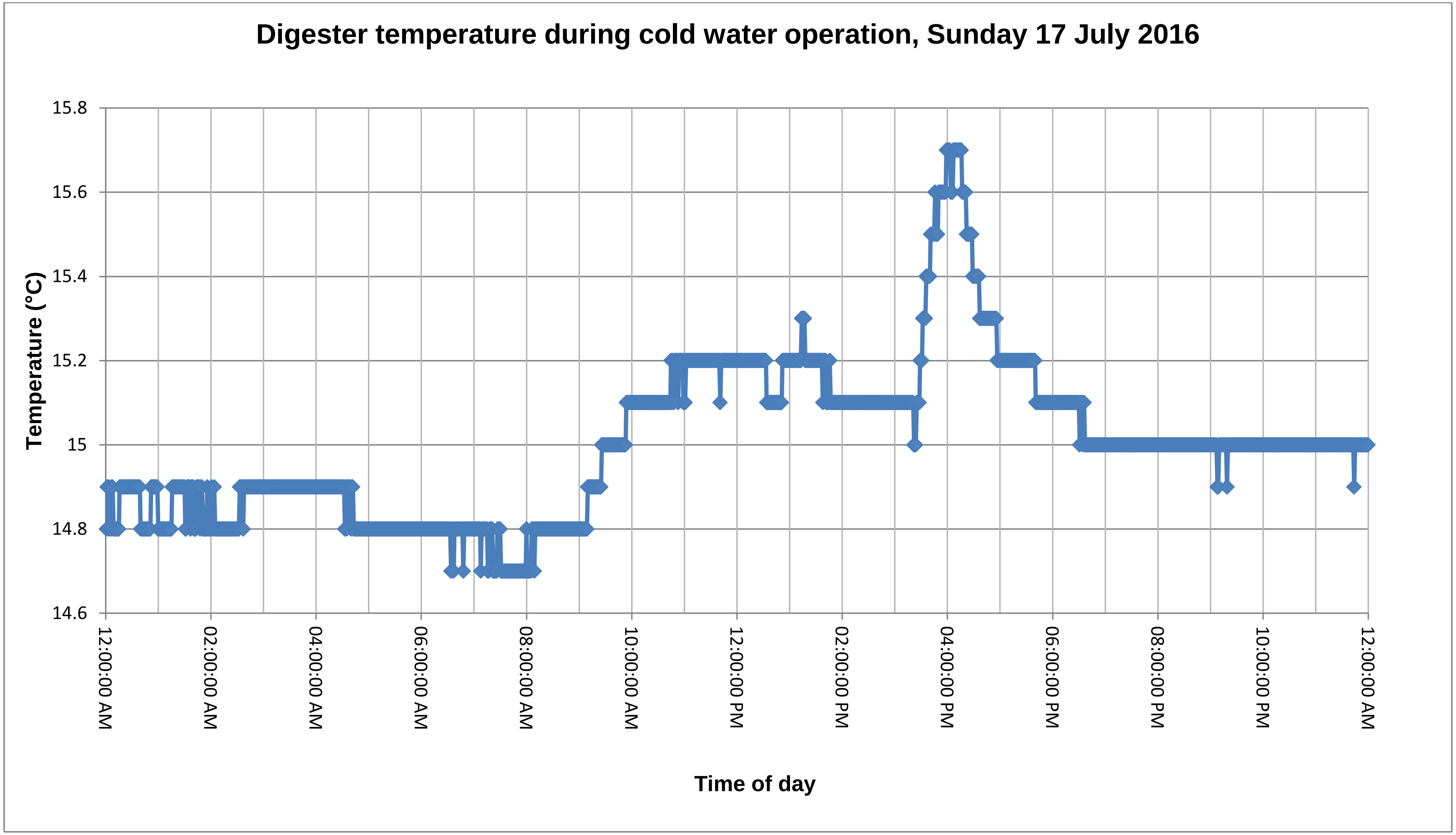


Figure 11-7: Digester temperature during cold water operation, Sunday 17 July 2016

12 Appendix E: Cold water operation data collected (2016)

Table 12-1: Cold water operation data

Date	CH4 (%)	O2 (%)	CO (ppm)	H2S (ppm)	P-start (kPa)	P-end (kPa)	ΔP (kPa)	V-start (m^3)	V-end (m^3)	ΔV (m^3)	T-burn (min)	pH	Temperature °C
20-Jun	55				3.2	2.1	1.1	1.319	1.374	0.055	14	6.42	15.7
21-Jun	54				3.4	2.6	0.8	1.374	1.428	0.054	17	6.3	15.8
22-Jun	54				3.3	2.4	0.9	1.428	1.484	0.056	16	6.24	15.4
23-Jun	55				3.2	2.3	0.9	1.484	1.539	0.055	18	6.26	15.2
24-Jun	56				3.4	2.3	1.1	1.539	1.594	0.055	16	6.29	15.6
25-Jun	56				3.3	2.2	1.1	1.594	1.65	0.056	15	6.27	14.9
26-Jun	56				3.4	2.4	1	1.65	1.707	0.057	16	6.25	15.1
27-Jun	57				3.4	2.2	1.2	1.707	1.767	0.06	18	6.24	14.8
28-Jun	56				3.2	2.3	0.9	1.767	1.823	0.056	15	6.3	15.1
29-Jun	57				3.6	2.4	1.2	1.823	1.882	0.059	17	6.34	14.7
30-Jun	57				3.4	2.3	1.1	1.882	1.943	0.061	15	6.32	15.3
01-Jul	58				3.3	2.1	1.2	1.943	2.001	0.058	16	6.28	15.2
02-Jul	58				3.2	2.3	0.9	2.001	2.061	0.06	18	6.33	15.5
03-Jul	58				3.1	2	1.1	2.061	2.118	0.057	15	6.32	15.1
04-Jul	59				3.3	2.3	1	2.118	2.177	0.059	16	6.34	15
05-Jul	59				3.6	2.5	1.1	2.177	2.243	0.066	17	6.36	15.3
06-Jul	58				3.7	2.5	1.2	2.243	2.311	0.068	18	6.36	15.6
07-Jul	59				3.9	2.8	1.1	2.311	2.381	0.07	17	6.34	15.4
08-Jul	59				4	3.1	0.9	2.381	2.447	0.066	16	6.37	15.6
09-Jul	60				4.1	3.2	0.9	2.431	2.504	0.073	19	6.41	15.1
10-Jul	60				3.9	3.1	0.8	2.504	2.575	0.071	18	6.45	15.5
11-Jul	61		11		4.2	3.3	0.9	2.575	2.642	0.067	16	6.51	15.1
12-Jul	62		20		4.1	3.3	0.8	2.642	2.702	0.06	17	6.59	15.2
13-Jul	63				4.1	3.3	0.8	2.702	2.762	0.06	16	6.62	15.3
14-Jul	65		18		4.3	3.2	1.1	2.762	3.282	0.52	24	6.64	15.5
15-Jul	65		20		4.1	3	1.1	3.282	3.351	0.069	18	6.81	15.1
16-Jul	64	23			4	3	1	3.351	3.411	0.06	17	6.63	15.2
17-Jul	64				4	3.3	0.7	3.411	3.469	0.058	16	6.71	15

13 Appendix F: Warm water operation data collected (2016)

Table 13-1: Warm water operation data, weeks 1-4

Date	CH4 (%)	O2 (%)	CO (ppm)	H2S (ppm)	P-start (kPa)	P-end (kPa)	ΔP (kPa)	V-start (m^3)	V-end (m^3)	ΔV (m^3)	T-burn (min)	pH	Temperature °C
18-Jul	65		25		4.1	3	1.1	3.469	3.56	0.091	22	6.73	16.9
19-Jul	65				3.9	2.8	1.1	3.56	3.624	0.064	16	6.66	16.8
20-Jul	72				3.8	2.6	1.2	3.624	3.677	0.053	14	6.64	17.7
21-Jul	72				3.8	3	0.8	3.677	3.729	0.052	13	6.7	18.2
22-Jul	73	32			4	2.8	1.2	3.729	3.796	0.067	16	6.68	18.4
23-Jul	68				4	2.6	1.4	3.796	3.883	0.087	23	6.58	17.8
24-Jul	70				4	2.8	1.2	3.883	3.953	0.07	20	6.72	17.3
25-Jul	74				4	2.8	1.2	3.953	4.019	0.066	16	6.72	18
26-Jul	68				4	2.9	1.1	4.019	4.075	0.056	15	6.68	18.4
					3.2	2.1	1.1	4.075	4.129	0.054	11		
27-Jul	70				3.4	1.8	1.6	4.129	4.175	0.046	14	6.74	18
					3	2	1	4.175	4.217	0.042	8		
28-Jul	71				3.8	2	1.8	4.217	4.257	0.04	9	6.69	19.7
					3	1.4	1.6	4.257	4.307	0.05	14		
29-Jul	74				3.2	1.8	1.4	4.307	4.347	0.04	11	6.7	20.3
					3.1	2	1.1	4.347	4.382	0.035	10		
30-Jul	74				3.6	1.2	2.4	4.382	4.467	0.085	24	6.76	19.6
31-Jul	75				3.6	1.6	2	4.467	4.551	0.084	14	6.6	18.8
01-Aug	75				3.3	1.7	1.6	4.551	4.593	0.042	14	6.56	18.9
					2.6	0.4	2.2	4.593	4.636	0.043	15		
02-Aug	75				3.1	1.6	1.5	4.636	4.668	0.032	15	6.54	19.4
					2.3	1.5	0.8	4.668	4.698	0.03	12		
03-Aug	74				3.7	0.7	3	4.698	4.78	0.082	26	6.57	18.7
04-Aug	74				3.2	1	2.2	4.78	4.848	0.068	22	6.68	18.9
05-Aug	77				3.8	0.9	2.9	4.848	4.941	0.093	27	6.6	19.2
06-Aug	76				3.8	1	2.8	4.941	5.059	0.118	35	6.58	18.8
07-Aug	77				3.6	2	1.6	5.059	5.13	0.071	19	6.56	18.2
08-Aug	75				3.8	2.3	1.5	5.13	5.175	0.045	12	6.63	18.5
					2.8	0.5	2.3	5.175	5.226	0.051	18		
09-Aug	77				3.7	1.1	2.6	5.226	5.327	0.101	30	6.66	18.3
10-Aug	76				3.8	2.2	1.6	5.327	5.374	0.047	14	6.77	18.9
					3.7	0.7	3	5.374	5.429	0.055	22		
11-Aug	78	13			3.7	1.5	2.2	5.429	5.489	0.06	20	6.7	19.4
					2.8	0.2	2.6	5.489	5.542	0.053	19		
12-Aug	76				3.5	2.1	1.4	5.542	5.592	0.05	15	6.7	19.6
					2.7	1.2	1.5	5.592	5.635	0.043	12		
13-Aug	77				3.8	1	2.8	5.635	5.763	0.128	37	6.65	19
14-Aug	76				4	0.7	3.3	5.763	5.895	0.132	36	6.69	18.3

Table 13-2: Warm water operation data, weeks 5 - 8

Date	CH4 (%)	O2 (%)	CO (ppm)	H2S (ppm)	P-start (kPa)	P-end (kPa)	ΔP (kPa)	V-start (m^3)	V-end (m^3)	ΔV (m^3)	T-burn (min)	pH	Temperature °C
15-Aug	75				3.2	1.8	1.4	5.895	5.94	0.045	15	6.71	18.7
					3.1	0.7	2.4	5.94	6.009	0.069	23		
16-Aug	77				3.3	1.2	2.1	6.009	6.07	0.061	22	6.65	19.4
					3.7	0.7	3	6.07	6.135	0.065	22		
17-Aug	77				3.4	1.3	2.1	6.135	6.185	0.05	23	6.7	20
					3.8	0.8	3	6.185	6.255	0.07	29		
18-Aug	74				3.6	1.3	2.3	6.255	6.327	0.072	25	6.8	20.2
					3.2	0.7	2.5	6.327	6.39	0.063	21		
19-Aug	74				3.7	2	1.7	6.39	6.451	0.061	20	6.8	20.2
					3.7	0.8	2.9	6.451	6.534	0.083	24		
20-Aug	70				4.7	0.8	3.9	6.534	6.7	0.166	51	6.63	20
21-Aug	65				4.8	0.9	3.9	6.7	6.81	0.11	48	6.65	19.1
					2	1	1	6.81	6.822	0.012	9		
22-Aug	62				3.2	1.2	2	6.822	6.902	0.08	26	6.6	19.5
					3.4	0.7	2.7	6.902	6.97	0.068	21		
23-Aug	62				3.7	2	1.7	6.97	7.042	0.072	22	6.56	20
					3.7	0.7	3	7.042	7.122	0.08	27		
24-Aug	61	0.2	37		3.8	2.1	1.7	7.122	7.22	0.098	29	6.53	20.3
					3.3	0.7	2.6	7.22	7.265	0.045	15		
25-Aug	61	0.7	13		4	2.5	1.5	7.265	7.376	0.111	32	6.51	20.5
					3.8	0.8	3	7.376	7.471	0.095	26		
26-Aug	61	0.1	18		3.8	1.4	2.4	7.471	7.568	0.097	32	6.62	20.9
					4	0.9	3.1	7.568	7.66	0.092	27		
27-Aug	61	0.1	12		4.7	0.7	4	7.66	7.861	0.201	56	6.66	20.4
28-Aug	61	0.1	13		4.2	0.8	3.4	7.861	8.008	0.147	43	6.65	19.7
29-Aug	62	0	11		3.6	1.6	2	8.008	8.068	0.06	16	6.59	20.1
					2.3	1	1.3	8.068	8.178	0.11	25		
30-Aug	62	0	11		3.9	1.2	2.7	8.178	8.308	0.13	42	6.61	19.2
					2.7	0.8	1.9	8.308	8.368	0.06	18		
31-Aug	63	0.4	8		4.1	0.8	3.3	8.368	8.476	0.108	43	6.61	18.5
					2.7	0.7	2	8.476	8.551	0.075	20		
01-Sep	62	0.3	8		3.1	1.5	1.6	8.551	8.622	0.071	23	6.59	18.2
					3.2	0.8	2.4	8.622	8.702	0.08	25		
02-Sep	63	0.4	8		3.7	0.8	2.9	8.702	8.8	0.098	30	6.64	17.9
					3	1.1	1.9	8.8	8.84	0.04	12		
03-Sep	63	0.6	7		4	1.1	2.9	8.84	8.937	0.097	30	6.61	17.8
04-Sep	64	0.4	9		4.2	0.8	3.4	8.937	9.091	0.154	41	6.62	17.7
05-Sep	64	0.1	9		3.7	0.7	3	9.091	9.204	0.113	39	6.6	18.2
					3.6	0.7	2.9	9.204	9.272	0.068	20		
06-Sep	64	0	14		4	0.8	3.2	9.272	9.358	0.086	26	6.75	19.2
					3.4	0.7	2.7	9.358	9.406	0.048	17		
07-Sep	63	0	9		3.9	0.8	3.1	9.406	9.527	0.121	32	6.74	20.1
					4.4	1.3	3.1	9.527	9.598	0.071	27		
08-Sep	62	0	11		4.6	1	3.6	9.598	9.688	0.09	29	6.71	20.6
					4	1.2	2.8	9.688	9.771	0.083	22		
09-Sep	62	0	14		4.9	1.1	3.8	9.771	9.899	0.128	42	6.57	20.9
					4.4	1.3	3.1	9.899	10.021	0.122	34		
10-Sep	62	0.1	90		4.9	1.3	3.6	10.021	10.144	0.123	43	6.62	20.7
					3	0.9	2.1	10.144	10.247	0.103	24		
11-Sep	62	0.2	70		4.5	0.5	4	10.247	10.364	0.117	43	6.54	20.1
					4	1	3	10.364	10.475	0.111	28		

14 Appendix G: Ambient temperature during operation

The data presented in this Appendix was collected from the Weather SA (weathersa: 2017), time-and-date (timeanddate: 2017) and accu-weather (accuweather: 2017) websites.

Table 14-1: Ambient temperature during cold water operation weeks 1 – 4

	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 1 cold water operation	20-Jun-16	6	15	10.5	
	21-Jun-16	4	16	10	
	22-Jun-16	3	20	11.5	
	23-Jun-16	5	26	15.5	
	24-Jun-16	9	17	13	
	25-Jun-16	10	19	14.5	
	26-Jun-16	9	18	13.5	**12.6**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 2 cold water operation	27-Jun-16	8	15	11.5	
	28-Jun-16	5	15	10	
	29-Jun-16	5	16	10.5	
	30-Jun-16	6	17	11.5	
	01-Jul-16	6	14	10	
	02-Jul-16	3	15	9	
	03-Jul-16	1	16	8.5	**10.1**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 3 cold water operation	04-Jul-16	1	24	12.5	
	05-Jul-16	10	16	13	
	06-Jul-16	5	15	10	
	07-Jul-16	1	16	8.5	
	08-Jul-16	7	15	11	
	09-Jul-16	9	20	14.5	
	10-Jul-16	6	29	17.5	**12.4**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 4 cold water operation	11-Jul-16	11	21	16	
	12-Jul-16	9	21	15	
	13-Jul-16	7	27	17	
	14-Jul-16	7	20	13.5	
	15-Jul-16	7	15	11	
	16-Jul-16	4	16	10	
	17-Jul-16	3	20	11.5	**13.4**

Table 14-2: Ambient temperature during warm water operation weeks 1 – 4

	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 1 warm water operation	18-Jul-16	9	19	14	
	19-Jul-16	14	17	15.5	
	20-Jul-16	14	17	15.5	
	21-Jul-16	12	17	14.5	
	22-Jul-16	8	16	12	
	23-Jul-16	7	15	11	
	24-Jul-16	3	15	9	**13.1**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 2 warm water operation	25-Jul-16	2	17	9.5	
	26-Jul-16	10	13	11.5	
	27-Jul-16	7	17	12	
	28-Jul-16	11	18	14.5	
	29-Jul-16	12	19	15.5	
	30-Jul-16	8	22	15	
	31-Jul-16	8	15	11.5	**12.8**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 3 warm water operation	01-Aug-16	8	19	13.5	
	02-Aug-16	6	21	13.5	
	03-Aug-16	10	17	13.5	
	04-Aug-16	9	18	13.5	
	05-Aug-16	7	18	12.5	
	06-Aug-16	12	19	15.5	
	07-Aug-16	10	18	14	**13.7**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 4 warm water operation	08-Aug-16	5	20	12.5	
	09-Aug-16	2	19	10.5	
	10-Aug-16	6	27	16.5	
	11-Aug-16	10	19	14.5	
	12-Aug-16	12	17	14.5	
	13-Aug-16	10	17	13.5	
	14-Aug-16	10	16	13	**13.6**

Table 14-3: Ambient temperature during warm water operation weeks 5 – 8

	Date	Min	Max	Daily Average	Weekly Average
Week 5 warm water operation	15-Aug-16	9	17	13	
	16-Aug-16	4	22	13	
	17-Aug-16	6	23	14.5	
	18-Aug-16	15	22	18.5	
	19-Aug-16	13	19	16	
	20-Aug-16	12	21	16.5	
	21-Aug-16	7	15	11	**14.6**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 6 warm water operation	22-Aug-16	9	17	13	
	23-Aug-16	10	19	14.5	
	24-Aug-16	7	22	14.5	
	25-Aug-16	5	19	12	
	26-Aug-16	7	29	18	
	27-Aug-16	11	28	19.5	
	28-Aug-16	10	19	14.5	**15.1**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 7 warm water operation	29-Aug-16	9	21	15	
	30-Aug-16	8	24	16	
	31-Aug-16	12	18	15	
	01-Sep-16	11	12	11.5	
	02-Sep-16	7	18	12.5	
	03-Sep-16	12	22	17	
	04-Sep-16	7	26	16.5	**14.8**
	Date	**Min**	**Max**	**Daily Average**	**Weekly Average**
Week 8 warm water operation	05-Sep-16	1	18	9.5	
	06-Sep-16	11	19	15	
	07-Sep-16	10	18	14	
	08-Sep-16	9	19	14	
	09-Sep-16	8	18	13	
	10-Sep-16	11	22	16.5	
	11-Sep-16	10	24	17	**14.1**