TEMPERATURE CONTROL SYSTEM DEVELOPMENT FOR BIOGAS PRODUCTION BY HYBRID SOLAR AND BIOGAS ENERGY

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ABSTRACT

Food waste has developed as an alternative for the production of renewable fuels such as biogas from AD. In relation to the biogas production rate, digester temperature setting is one of the very important factors for digester operation, especially in low temperature countries. In this study the effect of digester temperature on biogas and methane production efficiency in the AD of food waste was evaluated. The two-stage anaerobic digestion has a total reactor volume of 70 L. (acid reactor volume was 35 L. and methane reactor volume was 35 L.). There were incubated at mesophilic and thermophilic conditions for 25 days to determine a temperature profile for the AD process. The results of the laboratory-scale experiment, maximum biogas production occurred at 55°C (38.14 L. of biogas) for a period of 11 days when compared to the other temperatures. Second best was at 50°C (37.44 L. of biogas) for a period of 12 days, followed by 40°C (35.36 L. of biogas) for a period of 15 days respectively.

Heat required for the bioreactor was performed by a solar collector combined with biogas energy. Water contained within the jacket of the bioreactor was 35 liters and the bioreactor volume was 70 liters. Heating this volume of water to 35-60°C for the solar collector design. The solar collector consists of a galvanized steel flat plate of 4.98 m^2 dimensions. The absorber was insulated with a glass wool layer of 4 cm thickness at the bottom. All of these parts were arranged within a box of galvanized

steel base and glass top. The heat exchanger consists of a cylindrical storage tank of 35 L. The storage tank is wrapped with glass wool of 5 cm thickness. Cold water is supplied through the bottom of the flat plate collector and the hot water is retained in the storage tank of the heat exchanger. The outlet water from the bioreactor is fed back to the heat exchanger where it is reheated and then pumped back to the water jacket of the bioreactor. Heat of the bioreactor using solar energy can be approximated by first order dynamics and the night using biogas energy burn hot water. Two types of controllers were an on–off controller, and an analog PID controller. The on–off controller sensor was sensitive to small temperature variations.

Payback period of temperature control system for biogas production system was 5.88 year. Consideration total expenses cost per rate of system production and expense cost operating per rate of system production. The evaluation economic analysis of temperature control system for biogas production system was long time payback period because of the hot water system is very expensive. If the hot water system gets free, Payback period of biogas production system was 0.66 year.

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CHAPTER I

INTRODUCTION

Introduction

Due to upward trend in energy costs and problems associated with incineration of Municipal Solid Wastes (MSW), there have been developed many technologies that can partially dissolve the problems. Biological conversion of biomass to methane has received increasing attention in recent years. There are many renewable technologies for producing the energy from the solid wastes. Anaerobic Digestion (AD) has become an interesting technology and many research works are going on for the stability of this system. The anaerobic digestion of MSW is a process that has become a major focus of interest in waste management throughout the world.

Quick economic growth by industrialization of the developing countries in Asia. Uncontrolled urbanization has created serious problems of solid waste disposal. Many cities of the Developing Countries are facing problems with municipal solid wastes causes the serious environmental and health risks. Currently, biological treatment methods such as composting and AD offer the only route for recycling organic matter and nutrients from organic fraction of MSW.

One attractive application of anaerobic digestion is for treating municipal solid wastes in order to reduce the wastes to be disposed and to produce renewable energy. Solid wastes in Developing Countries have become great problem because the amounts of the solid wastes are increasing day by day due to rapid population growth and urbanization. The availability of landfill location are declining due to conventional disposal methods and the opening of new landfill location are limited due to legal and financial problems.

Since the municipal solid wastes consist of high proportion of organic fraction and it is understood as organic-biodegradable waste with moisture content around 85-90 %. These wet streams of wastes are not so viable for incineration to produce energy. The incineration generates the air pollutants such as nitrogen dioxide, sulfur dioxide and greenhouse gases. Around the world particularly in urban areas, pollution of air and water from municipal solid wastes continues to grow. It has become great threat to environmental and public health. Anaerobic digestion not only provides pollution prevention, but also allows for energy, compost and nutrient recovery. In life cycle assessment using eco-indicator method, AD also showed an excellent LCA performance compared to other treatment technology such as composting, incineration.

Anaerobic digestion is an engineered methanogenic decomposition of organic matter in the absence of free oxygen and involves a consortium of different anaerobic microorganism which transforms organic matter into useful energy. Application of anaerobic digestion for waste treatment produces significant benefits that include both energy production and energy conservation. The production of biogas from solid waste materials for using as a fuel source succeeds anaerobic digestion as a sustainable technology for renewable energy source. The anaerobic digestion of the Organic Fraction of Municipal Solid Wastes (OFMSW) yields much better results in thermophilic temperature conditions than in mesophilic temperature conditions.

A given amount of volatile solids of a particular waste can be converted to a maximum amount of biogas at a given temperature provided optimum conditions are prevalent. This conversion can be accounted by two factors i.e. biodegradability at a specified temperature and operating conditions, reactor configuration, the flow pattern within the digester and digestion stage.

It is difficult to summarize on anaerobic digestion of solid waste with similar experimental set up. This difficulty is due to the great diversity of reactor designs which is suited by a large variation of waste composition and choice of operational parameters. The evaluation of the reactor designs can be made in terms of the rate, stability and total of biochemical reactions. The methane of organic wastes is attained by a sequence of biochemical transformations, which can be mainly separated into two steps. The first step consists of hydrolysis, liquefaction and acidification whereas the second step involves the transformation of acetate, hydrogen and carbon dioxide into methane.

Depending upon the number of stages and concentration of total solids, the design of reactor is classified as single system and multi stage system. Similarly the anaerobic rectors can be operated into different.

According to previous studies, there was a problem of low biogas yield, low methane composition and lower removal of volatile solids in the continuous anaerobic digestion system. The problem was due to the design configuration of the reactor. In this study the problems as said above has solved by modifying the design of reactor and the optimization of operational parameters such as organic loading rates, retention time for maximum volatile solids reduction has conducted.

Propose of the study

The main propose of this research is to development temperature control system for biogas production by hybrid solar and biogas energy. The specific objectives of this study are as follow:

1. To determine the biogas tank temperature that suitable for biogas production.
2. To develop the temperature control system for biogas production.
3. To analyze the economic parameter of biogas temperature control system.

Scope of the study

In this research will use the organic solid wastes from restaurant in Nuresuan University. The digester laboratory scale uses two-stage-anaerobic digestion system. And the organic waste is filtered by sieve tray.

Keywords

Biogas / Temperature Control / Hybrid solar and biogas energy

Benefit of the study

1. To use temperature control to various biogas plant for increasing the volume of gas.
2. Knowing the performance of biogas system by temperature control with solar collector and biogas burning.
3. Using the model of temperature control biogas production for application with solar and biogas.

CHAPTER II

LITERATURE REVIEW

Anaerobic Digestion Process

The process of biogas formation is a result of linked process steps, in which the initial material is continuously broken down into smaller units. Specific groups of micro-organisms are involved in each individual step. These organisms successively decompose the products of the previous steps. The simplified diagram of the AD process, shown in Figure 1, highlights the four main process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

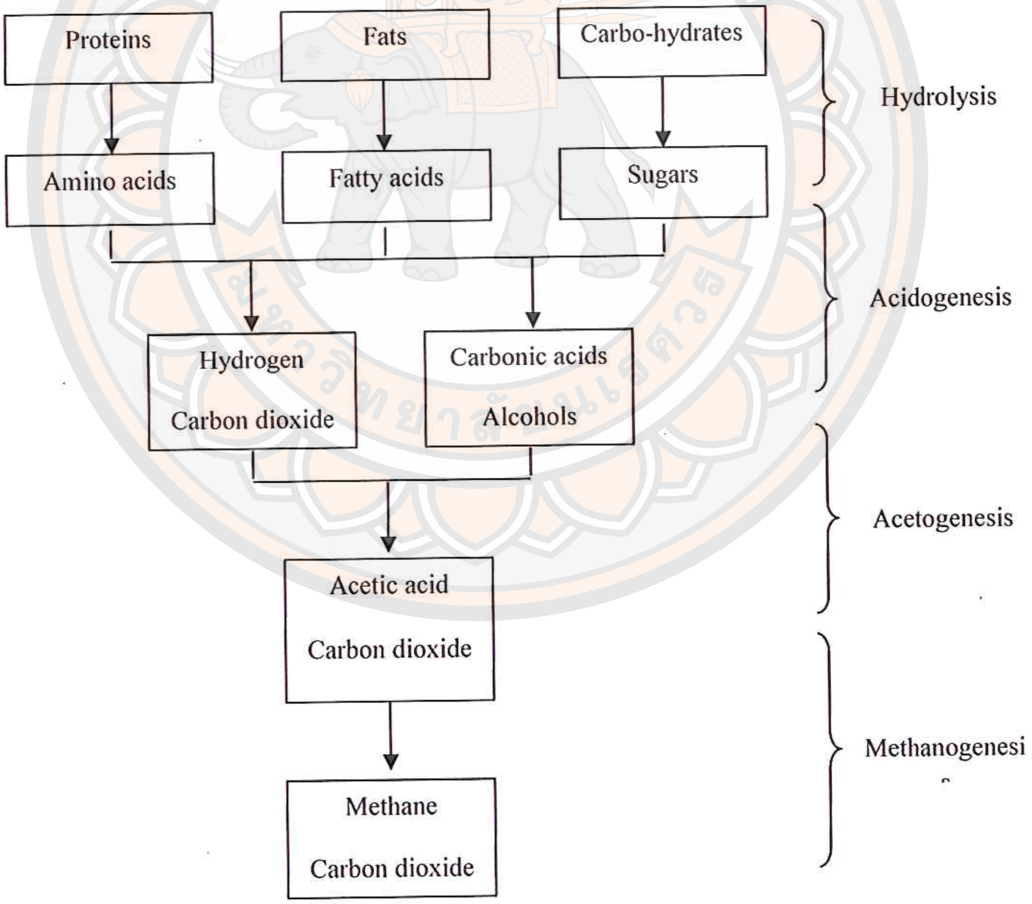

Figure 1 The main process steps of AD

Source: Al Seadi T., 2001

The process steps quoted in Figure 1 run parallel in time and space, in the digester tank. The speed of the total decomposition process is determined by the slowest reaction of the chain. In the case of biogas plants, processing vegetable substrates containing cellulose, hemi-cellulose and lignin, hydrolysis is the speed determining process. During hydrolysis, relatively small amounts of biogas are produced. Biogas production reaches its peak during methanogenesis.

Hydrolysis

Hydrolysis is theoretically the first step of AD, during which the complex organic matter (polymers) is decomposed into smaller units (mono- and oligomers). During hydrolysis, polymers like carbohydrates, lipids, nucleic acids and proteins are converted into glucose, glycerol, purines and pyridines. Hydrolytic microorganisms excrete hydrolytic enzymes, converting biopolymers into simpler and soluble compounds as it is shown below:

$$\text{Lipids} \xrightarrow{\text{lipase}} \text{fatty acids, glycerol}$$

$$\text{Polysaccharide} \xrightarrow{\text{Cellulose, cellobiase,xylanase,amylase}} \text{monosaccharide}$$

$$\text{Protein} \xrightarrow{\text{protease}} \text{amino acids}$$

A variety of microorganisms is involved in hydrolysis, which is carried out by exoenzymes, produced by those microorganisms which decompose the undissolved particulate material. The products resulted from hydrolysis are further decomposed by the microorganisms involved and used for their own metabolic processes.

Acidogenesis

During acidogenesis, the products of hydrolysis are converted by acidogenic (fermentative) bacteria into methanogenic substrates. Simple sugars, amino acids and fatty acids are degraded into acetate, carbon dioxide and hydrogen (70%) as well as into volatile fatty acids (VFA) and alcohols (30%).

Acetogenesis

Products from acidogenesis, which cannot be directly converted to methane by methanogenic bacteria, are converted into methanogenic substrates during acetogenesis. VFA and alcohols are oxidised into methanogenic substrates like acetate, hydrogen and carbon dioxide. VFA, with carbon chains longer than two units and alcohols, with carbon chains longer than one unit, are oxidized into acetate and hydrogen. The production of hydrogen increases the hydrogen partial pressure. This can be regarded as a waste product of acetogenesis and inhibits the metabolism of the acetogenic bacteria. During methanogenesis, hydrogen is converted into methane. Acetogenesis and methanogenesis usually run parallel, as symbiosis of two groups of organisms.

Methanogenesis

The production of methane and carbon dioxide from intermediate products is carried out by methanogenic bacteria. 70% of the formed methane originates from acetate, while the remaining 30% is produced from conversion of hydrogen (H_2) and carbon dioxide (CO_2), according to the following equations:

$$\text{Acetic acid} \xrightarrow{\text{Methanogenic bacteria}} \text{methane + carbon dioxide}$$

$$\text{Hydrogen + carbon dioxide} \xrightarrow{\text{Methanogenic bacteria}} \text{methane + water}$$

Methanogenesis is a critical step in the entire anaerobic digestion process, as it is the slowest biochemical reaction of the process. Methanogenesis is severely influenced by operation conditions. Composition of feedstock, feeding rate, temperature, and pH are examples of factors influencing the methanogenesis process.

Digester overloading, temperature changes or large entry of oxygen can result in termination of methane production.

Process parameters

With all biological processes, the constancy of the living conditions is of importance. A temperature change or changes in the substrates or the substrate concentration can lead to shutdown of the gas production. It can last up to three or even more weeks, until the ecological system has adapted to the new conditions and starts biogas production again without any intervention from outside. But in the case of human interference it can take a further three weeks.

The microbial metabolism processes are dependent on many parameters (Table 1), so that, for an optimum fermenting process, numerous parameters must be taken into consideration and be controlled. Furthermore, the environmental requirements of the fermentative bacteria, by which the hydrolysis and acidification of the substrates occur, differ from the requirements of the methane–forming microorganisms.

Table 1 Environmental requirement.

Parameter	Hydrolysis /acidogenesis	Methane formation
Temperature	25–35°C	Mesophilic: 32–42°C Thermophilic: 50–58°C
pH value	5.2–6.3	6.7–7.5
C:N ratio	10–45	20–30
DM content	<40% DM	<30% DM
Redox potential	+400 to−300 mV	<−250 mV
Required C:N:P:S ratio	500 : 15 : 5 : 3	600 : 15 : 5 : 3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se

Optimum environmental conditions for all microorganisms involved in the degradation can only be set in a two-stage plant with one stage for hydrolysis /acidification and one stage for acetogenenis /methanation. Provided that the complete degradation process has to take place in the same reaction system (1-stage process), the environmental requirements of the methanogenics must be fulfilled with priority, because these would otherwise have no chance of survival within the mixed culture because of their lower growth rate and higher sensitivity to environmental factors. But the following divergences from this rule are to be taken into consideration.

1. With lignocellulose-containing substrates, the hydrolysis limits the process and therefore needs higher priority.

2. With protein - containing substates, the pH optima are the same in both stages, so that a single - stage plant is quite sufficient.

3. With fats, the hydrolysis proceeds more rapidly with increasing emulsification (bioavailability), so that the acetogenesis is limiting. A thermophilic catabolism of fat is to be preferred.

Parameter: hydrogen partial pressure

A narrow spatial symbiosis is necessary for an undisturbed process between the H_2-producing acetogenic bacteria and the H_2 consuming-methanogenics.

If generally a biological reaction is to take place, the reaction must be exergonic; i.e., the free energy must be negative. The hydrogen concentration should be well alanced: on the one hand methanogenics need enough hydrogen for the methane production. On the other hand the hydrogen partial pressure must be so low that acetogenic bacteria are not surrounded by too much hydrogen and consequently stop the hydrogen production. The maximum acceptable hydrogen partial pressure depends on the species of bacteria and also on the substrates.

For the anaerobic conversion of propionate (salt of the propionic acid) via acetic acid and hydrogen/carbon dioxide to methane, this energetic window is especially small, as Figure 2 shows. The degradation of propionic acid can be taken as a measure of the productivity of the plant, because this decomposition is often the limiting factor of an anaerobic fermentation in practice.

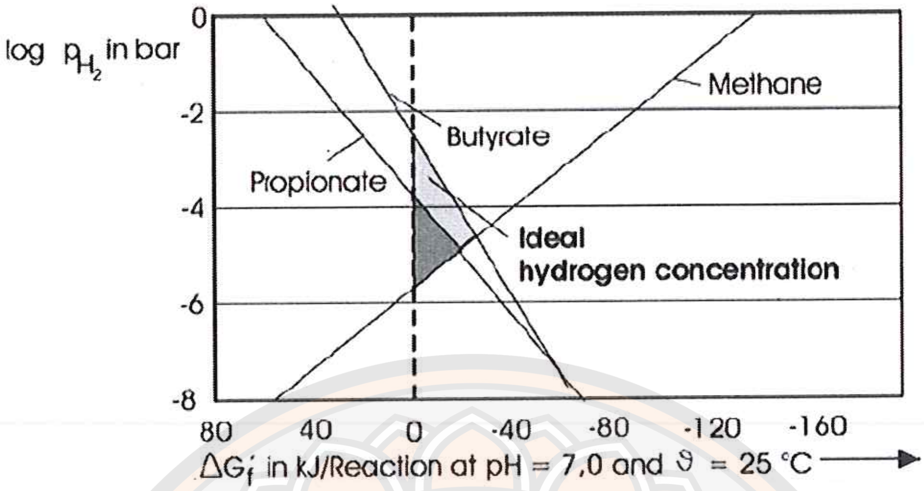

Figure 2 **Influence of the hydrogen partial pressure pH_2 on the energy release $\Delta G_f'$ during acetogenesis and methane formation from carbon dioxide and the hydrogen**

Source: Dieter Deublein and Angelika Steinhauser, 2010

Parameter: concentration of the microorganisms

Methanogenic microorganisms have a long regeneration time in general (Table 2). To avoid washing out from the reactor, hydraulic residence times must be at least 10–15 days with reactor systems which do not have facilities for retaining and returning biomass.

In comparison with this, the regeneration times of hydrolytic and acid–forming bacteria are significantly shorter, so that with them there is hardly any risk of washout.

The low growth rate of the methanogenics means that for biogas plants a relatively long start-up phase of up to 3 months is required, because the amount of inoculating sludge necessary to start the plant at full capacity immediately is mostly not available and has to be built up in the starting phase.

Table 2 Time of regeneration of different anaerobic microorganism in comparison to aerobic MO

Anaerobic microorganism	Time of regeneration
Acidogenic bacteria	
Bacterioids	<24 h
Clostridia	24–36 h
Acetogenic bacteria	80–90 h
Methanogenic bacteria	
Methanosarcina barkeri	5–16 d
Methanococcus	ca. 10 d
Aerobic microorganism	
Escherichia coli	20 min
Active sludge bacteria	2 h
Bacteria living on earth	1–5 h

Parameter: type of substrate

The substrate determines the rate of the anaerobic degradation and must be taken into consideration in the process technology and process operation. If a substrate component of vital importance runs out, the microorganisms stop their metabolism. Therefore, it is often necessary to feed possibly lacking substances (carbohydrates, fat, proteins, mineral substances, and trace elements) as well as the substrate.

Sugar, for example, hydrolyzes and acidifies within very short time. The degradation of cellulose proceeds considerably more slowly, depending on the fraction in the form of lignin. At long residence times of 20 and more days, even medium - heavy and heavy degradable materials hydrolyze and are eventually metabolized to methane.

According to the composition of the substrates, intermediate products of the decomposition can also limit or inhibit the degradation. Thus, for example, the degradation of fats can give rise to fatty acids, which limit the further degradation. With the decomposition of proteins, methane fermentation can be restrained by the formation of ammonia and hydrogen sulfide.

Parameter: specific surface of material

To support a biochemical reaction a material surface as big as possible is necessary. The material surface often varies proportionally to the square of the particle size. In order to increase the material surface, comminution of the biomass is in many cases recommended before fermentation.

Figure 3 clearly demonstrates the advantages of comminution in an agitated ball mill (RWKM) for biogas production. The degradation process is accelerated in the first few days as a result of the mechanical treatment and the biogas yield for the whole time of digestion is higher. Already in the first few days the biogas development is more vigorous and the resulting difference of the biogas yield is maintained until the end of the degradation, here after 25 days.

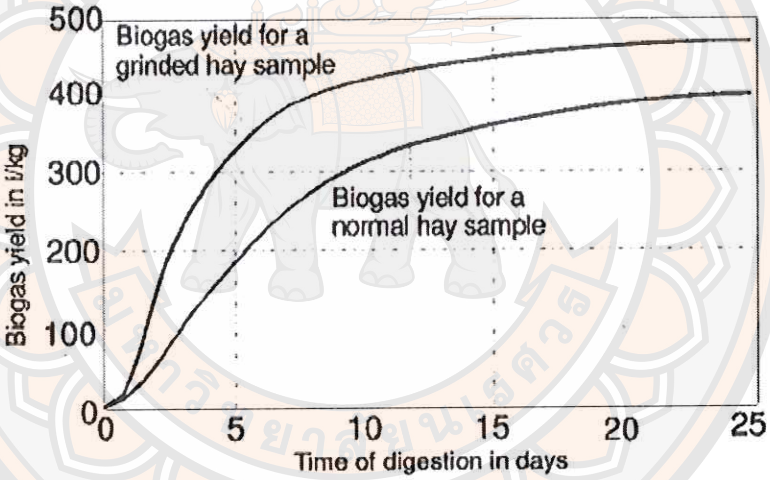

Figure 3 Biogas yield from hay with and without being grinded in an agitated ball mill

Source: Dieter Deublein and Angelika Steinhauser, 2010

Comminution does not have a big influence on the biogas yield when easily degradable materials (95% or 88% grade of decomposition) are used, which have only a very low content of structural materials (cellulose, lignin, etc.). Such material is easy accessible for the microorganisms (Figure 4).

With substrates like hay and foliage, which are rich in structured materials and enable only a grade of decomposition of ca. 50% without comminution, the biogas yield can be increased by up to 20% depending on the grade of comminution (Figure 5). The increase in the particle surface area and the loosening of the fiber structure are the reasons. With sunflower kernels, for example, the destruction of the outer layer of the kernels is decisive.

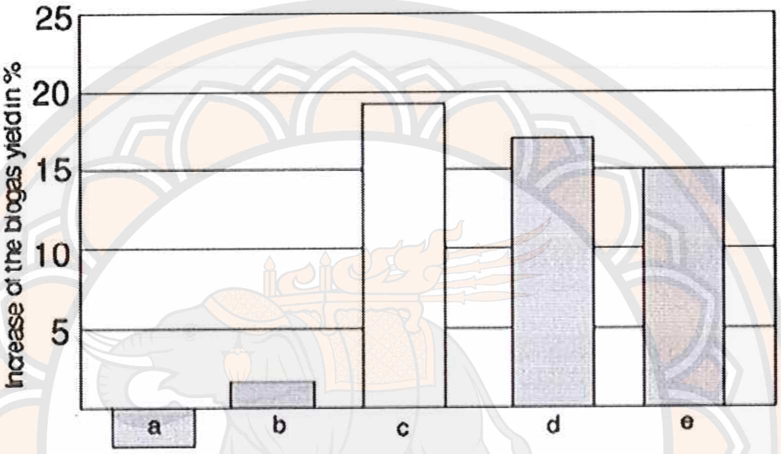

Figure 4 Increase of the biogas yield through grinding (a: mix of apples, potatoes and carrots; b: meat; c: sunflower kernels; d: hay; e: leaves)

Source: Dieter Deublein and Angelika Steinhauser, 2010

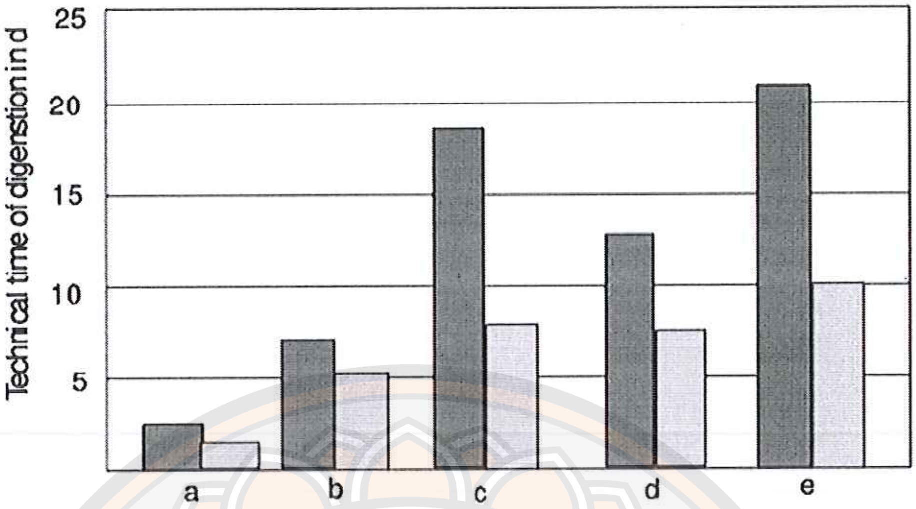

Figure 5 **Influence of the grinding on the technical time of fermentation for different substrates (a: mix of apples, potatoes, and carrots; b: meat; c: sunflower kernels; d: hay; e: leaves) left columns: without grinding, right columns: with grinding.**

Source: Dieter Deublein and Angelika Steinhauser, 2010

The technical residence time is the time, at which 80% of the maximum biogas yield is reached. A tendency can be clearly seen, in the case of all substrates, for the technical residence time to be reduced as a result of comminution. The best reduction is achieved with substrates which have the longest technical residence time without comminution. The technical residence time of different substrates can be equalized by comminution.

The degree of decomposition can be defined as the ratio of the actual chemical oxygen demand (COD) to the maximum achievable COD (COD_{max}), corresponding to the chemical oxygen demand for the entire degradation of all organic components in the sample, as measured by a test in which hay haulms of different length were fermented once comminuted and once not comminuted (Figure 6).

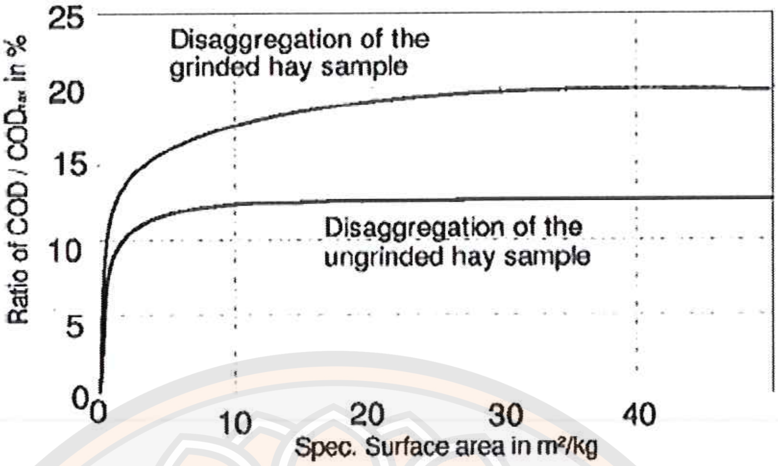

Figure 6 Influence of the specific surface area on the release of organic acids within 10 min (given as organic matter measured as COD)

Source: Dieter Deublein and Angelika Steinhauser, 2010

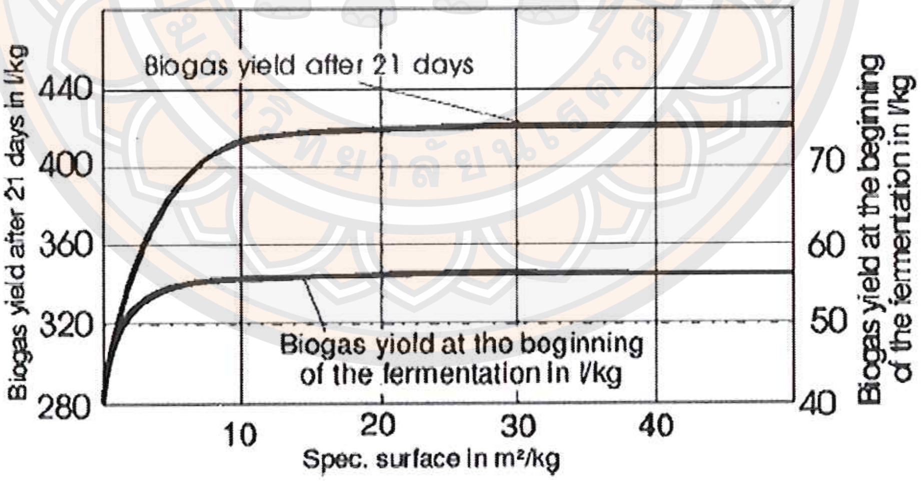

Figure 7 Influence of the specific surface on the biogas yield $v_{g,zu}$ after 21 days of fermentation and at the beginning of the fermentation

Source: Dieter Deublein and Angelika Steinhauser, 2010

It can be seen that, with all hay haulm fractions, there is a relatively high proportion of quickly dissolvable substances. Even with the untreated fraction, more than 10% of the organic material changes into the dissolved form. Figure 7 shows the biogas yield at the beginning of the fermentation and after 21 days as a function of the specific surface for hay fractions.

The bigger the specific surface of the biomass, the higher is the biogas yield, but the relationship is not linear. The comminution of fine particles contributes less than the comminution of big particles.

It can be assumed that the increase in the specific surface increases especially the microbiological degradation processes and not the physical solution processes, which would start after a short time.

Parameter: disintegration

The destruction of the cell structure and, with higher energy impact, even of the cell walls, is called "disintegration" or "cell disruption". There are many reasons for adding disintegration devices to a normal biomass fermentation plant, but there are also some reasons against it. Today, thisintegration is mainly recommended for sewage gas production and is applied sporadically.

Reasons for the application of the disintegration are discussed below.

Disintegration increases the degree of decomposition and decreases the amount of sewage sludge.

The disintegration brings, above all, advantages with biomasses that are difficult to destroy (Figure 8). For example, excess sludge can be degraded more easily, effectively around 10–30%, with a residence time of 15 days in the bioreactor. This is due to the fact that the time for hydrolysis is shortened as a function of sludge age and the fraction of facultative anaerobic microorganisms. The influence of the disintegration is more important if shorter degradation times must be used.

The dry matter of sewage sludge can be reduced to 50%, because parts of it are diluted. In total, the content of organic dry matter in the sludge is slighty increased.

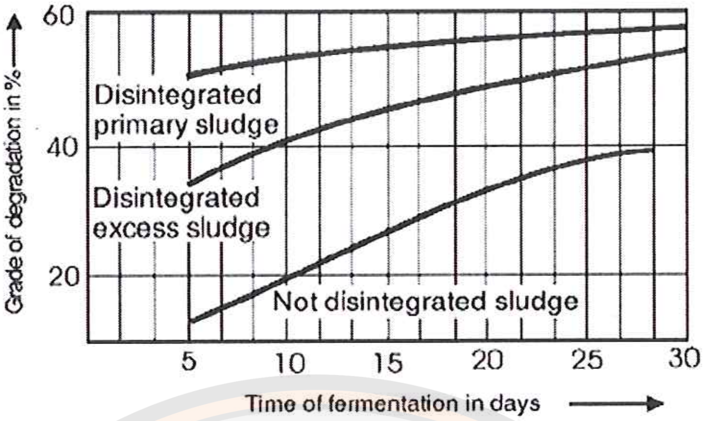

Figure 8 Influence of disintegration on the degradability of different sewage sludges

Source: Dieter Deublein and Angelika Steinhauser, 2010

Disintegration increases the biogas yield.

The biogas yield of sewage sludge can be increased to abt. 350–375 L kg^{-1} oDM by disintegration (Figure 9).

If degraded sludge is held for 1h at 70^{o}C and then further degraded for another 15 days, an increase in the biogas yield of 25% can be achieved. When decomposing at an elevated temperature of 55^{o}C, after thermal disintegration an increase in the gas yield of up to 50% is even possible.

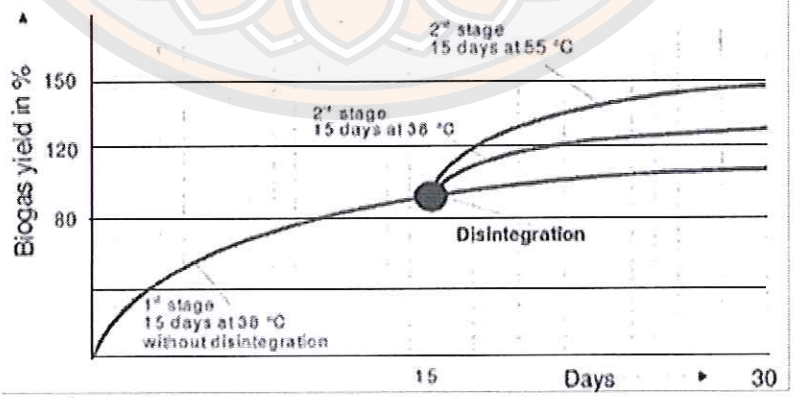

Figure 9 Biogas produced from 1 kg organic matter

Source: Dieter Deublein and Angelika Steinhauser, 2010

The products of disintegration can serve as a hydrogen source or electron donor for the denitrification of waste water.

With the excess water of disintegrated sewage sludge, the same or even higher velocities of denitrification can be achieved in comparison to using acetate as the hydrogen source (Table 3) for waste water treatment.

Table 3 Rate of denitrification of different substrates.

H sources acting as electron donors for denitrification	**Rate of denitrification [Mg NOx - N/h]**
Disintegrated sewage sludge	3.0–4.8
Synthetic waste water according to DEV L24	4.0
Communal waste water	4 0
Acetic acid	3.9

Disintegration lowers the viscosity of the sludge.

On degradation of the biomass the viscosity decreases of the factor of 30. The heat transfer and the mixing are thereby improved considerably. Less attachment to the heating surfaces is observed.

The sedimentation behavior of the sewage sludge is improved.

The sedimentation behavior of the sludge is improved by up to 70%. Hence, disintegration is to be recommended, especially with bulking sludge, because it sediments with difficulty because of its high content of filamantous microorganisms.

The formation of floating sludge can be considerably reduced and even sometimes completely avoided.

Particularly with the degradation of sewage sludge, it often happens that all the sludge ascends as floating layer to the surface. Then the percentage of the swimming sludge to the total amount of sludge is AVA_{FS} = 100%. The ascent of sludge can be prevented by disintegration (Figure 10). Then the value rises to only AVA_{FS} = 40% after the first five days after feeding the bioreactor because of strong gas development and then decreases rapidly with decrease of the biogas production.

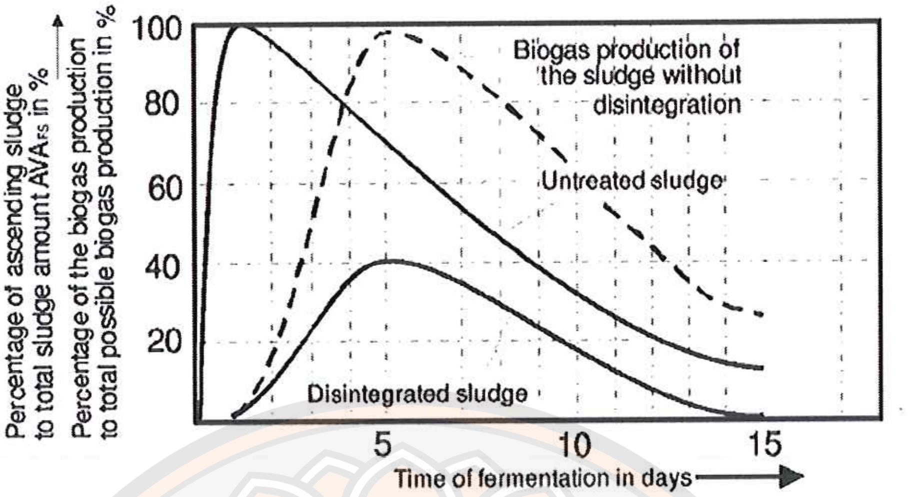

Figure 10 **Percentage in the bioreactor of ascending sludge AVA_{FS} and biogas production depending on disintegration**

Source: Dieter Deublein and Angelika Steinhauser, 2010

Foaming in the bioreactor (caused by filamentous organisms from the activated sludge tank) can be combated by disintegration.

If the formation of foam is caused through a high proportion of filamentous microorganisms in the excess sludge, the voluminous flake structure is destroyed by the disintegration, and therefore the possibility that gas bubbles are attached to the flakes is reduced. The amount of floating sludge in the digestion tank can be reduced.

Disadvantages of disintegration are discussed below.

Disintegration affects the dehydratability, and the demand on flocculants is thus increased.

The sludge flakes are chopped up by the disintegration and are more difficult to dehydrate, because, among other things, cell - internal polysaccharides are released which are difficult to degrade because of their complex structure. Therefore, after disintegration and degradation, on average ca. 40% more flocculants are needed for dehydration.

Disintegration increases the back load of the water treatment plant with nitrogen, carbon, heavy metals, and phosphates.

As a result of the improvement of the degradation by the disintegration of proteins released from the cells, an increased nitrogen back load of approx. 30% is to be anticipated with the sludge pumped back to the waste water facilities, because ammonium remains as an end product of the protein degradation in the water (see Table 4).

Table 4 Influence of the disintegration upon the dehydratability and back load after an anaerobic fermentation

Sample	Unit	Not disintegrated	Mechanically disintegrated	Average/average relative change
Degradability A_s	%	0	43–57	53%
Time of fermentation	d	13–21	13–20	17 d
Degree of degradation	%	28–34	33–49	+19%
Requirement for flocculants (polymers)	g/kg	5.0–6.5	6.7–9.0	+42%
Residual dry matter	g/kg	58–154	61–145	−6%
TKN nitrogen content, after Kjeldahl.	mg L^{-1}	156–680	204–822	+28%
Organic matter after filtration	mg L^{-1}	35–253	46–283	+38%
$P0_4$.P	mg L^{-1}	24–251	20–208	−9%

The back load of carbon compounds is raised to more than 40%, and the BOD_5 increases by 30–40%.

Immediately after the disintegration, heavy metals are to be measured in the liquid phase. During the subsequent sludge stabilization the heavy metals are adsorbed again in the matrix of the sludge. The increased degradation of organic matter causes the concentration of the heavy metals in the residue to rise.

The back load on the sewage treatment plant with phosphate is different. As long as enough cations exist for precipitating reactions, there is no increased back load with phosphates in consequence of mechanical disintegration.

Disintegration increases the filtration resistance.

After degradation, the decomposed sludge has to be dehydrated. This can be achieved by belt - type presses or chamber filter presses. Depending on the process of disintegration, the filtration is more or less impaired.

Disintegration increases the power consumption of the complete sewage treatment plant.

In general but not always, the power consumption increases with increasing degree of disintegration (Figure 11), of course more or less depending on the process of disintegration and particularly on the heat developed in the process. A nearly complete disintegration (> 95%) of microorganisms has now been achieved by means of agitated ball mills, ultrasonic treatment, and a high – pressure homogenizer.

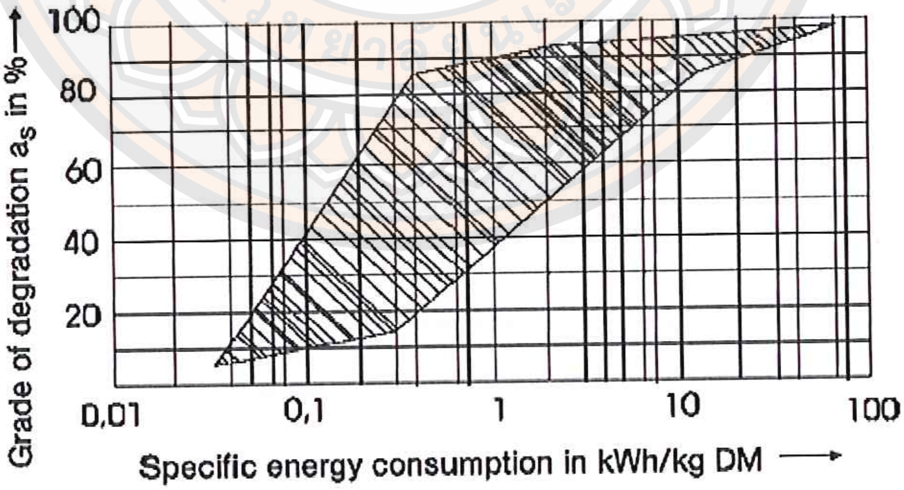

Figure 11 Energy consumption during disintegration

Source: Dieter Deublein and Angelika Steinhauser, 2010

Disintegration leads to considerable erosion or corrosion problems.

For disintegration, the substrates have to be stressed, either by high temperatures, chemical or enzymatic attacks, high stress factors, or other means. These forces also affect the machines and containers and shorten their life span.

Parameter: cultivation, mixing, and volume load

The start - up phase of an anaerobic plant often lasts 2–4 months (Figure 12). The start-up of the plant usually has a long-term effect on the biocenosis. The start-up even can fail completely; i.e., the bioreaction does not work and biogas is not produced. To avoid these problems, the hydrolyzer and the methane reactor are often inoculated with anaerobic sludge from other fermentation plants. The mixing of the reactor has to be carried out very carefully:

1. On the one hand, each individual microorganism must be supplied evenly with nutrients and the metabolism products have to be removed evenly also, which can be achieved by smooth agitation. On the other hand, both movements can be blocked, e.g., by a layer of H_2 around the microorganism, which has to be destroyed by heavy agitation.

2. Fresh substrate may have to be mixed with degraded substrate in order to inoculate the fresh substrate with active bacteria.

3. The biogas must be removed effectively from the reactor.

4. The symbiosis from acetogenic and methanogenic microorganism must not be disturbed.

5. The microorganisms are actually stress - sensitive and can be destroyed by too strong agitating.

6. Foaming due to a too intensive gassing can be prevented by adequate agitation.

7. Temperature gradients in the bioreactor result in lower reaction efficiency.

8. Floating and sinking layers have to be destroyed.

9. The energy consumption must be minimized

10. Solids must be prevented from reaching the discharge, as they must be filtered out afterwards.

Usually, a careful but intensive mixing action is choosen.

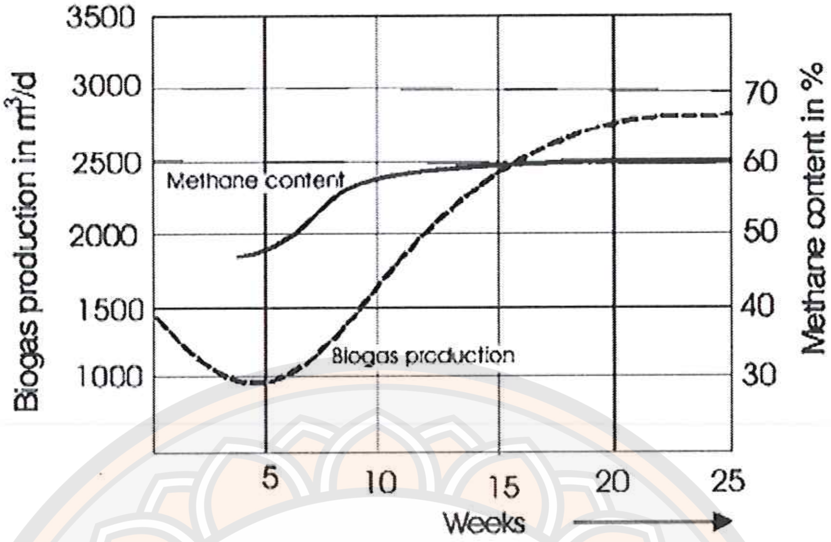

Figure 12 Gas production and methane content of the gas during start – up

Source: Dieter Deublein and Angelika Steinhauser, 2010

The volume load depends particularly on the temperature, the organic dry matter in the substrate, and the residence time (Figure 13).

With more than 12% solids in the substrate, gas production is impaired. For economic reasons, the solid content should not exceed 30% DM, because

1. a too low water content retards any cell growth
2. the material transfer within the substrate becomes a limiting factor
3. the biomass cannot be pumped or mixed any longer.

With too low a load, on the other hand, the process works, but it does not work economically, because too much water is passed.

In order to avoid a locally excessive volume load, the bioreactor should be fed frequently, e.g., twice daily or continuously.

For economic reasons, biogas reactors are designed so that 75% of the maximum degradable organic matter is actually decomposed.

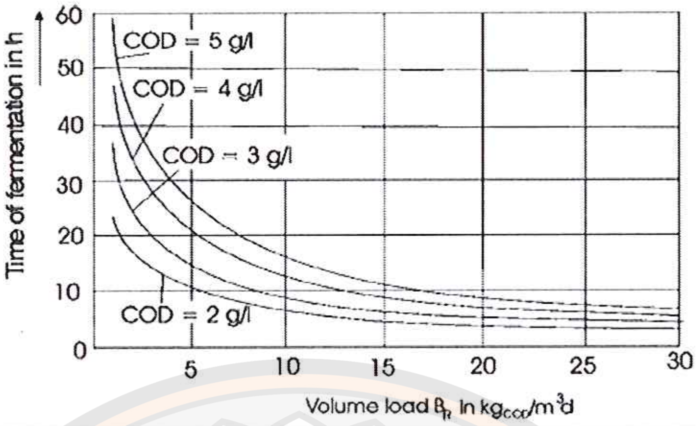

Figure 13 Maximum load of the reactor depending on the time of fermentation at a given concentration

Source: Dieter Deublein and Angelika Steinhauser, 2010

Parameter: light

Light is not lethal for methanogenics, but severely inhibits the methanation. The methane formation should therefore take place in absolute darkness.

Parameter: temperature

The temperature shows two optima for acidifying bacteria; a smooth one at abt. 32–42°C for mesophilic microorganisms and a sharp one at 48–55°C for thermophilic microorganisms (Figure 14).

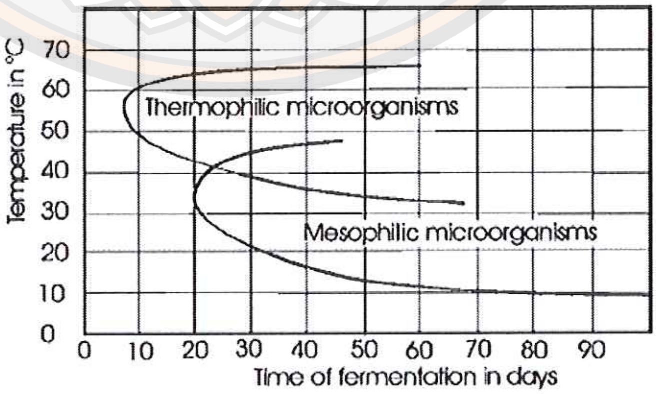

Figure 14 Influence of the temperature upon the time of fermentation

Source: Dieter Deublein and Angelika Steinhauser, 2010

Most of the methanogenic microorganisms belong to the mesophilics. Only a few are thermophilic. A few others are able to produce methane even at low temperatures (0.6 –1.2°C), e.g., on the surface of permafrost soils. In laboratory tests, methane formation could be proven also with temperatures below freezing, i.e. down to −3°C. In general, the lowest temperature at which microorganisms grow is −11°C. Below −25°C, even the enzyme activity succumbs. Methanogenics are sensitive to to rapid changes of temperature. Thermophilic methanogens are more temperature - sensitive than mesophilics. Even small variations in temperature cause a substantial decrease in activity. Therefore, the temperature should be kept exactly within a range of +/−2°C. Otherwise, gas losses of up to 30% have to be taken in consideration. Particularly critical for mesophilics are temperatures in the range of 40–45°C, because in that range they lose their activity irreversibly.

Under mesophilic operating conditions, the inhibition of ammonium is reduced because of the lower content of inhibiting free ammonia.

In general, it has to be menshioned that the energy balance is better in the mesophilic range than in the thermophilic range.

The thermophilic mode of operation results in ca. 50% higher rate of degradation, and, particularly with fat-containing materials, a better microbial availability of the substrates and thus a higher biogas yield.

Epidemics and phytopathogenic germs are inactivated by higher process temperatures, so that special hygienic procedures are not necessary when using a temperature >55° and a material retention time of >23h.

Oxygen is less soluble in the thermophilic temperature range, so that the optimal anaerobic operating conditions are reached more quickly.

In many two - stage plants, therefore, different temperatures are applied at the two stages. There are good reasons to drive the methanation thermophilically and the hydrolysis mesophilically. But, depending on the substrate, it can also be favorable to operate the hydrolysis at higher temperatures than the methanation.

Parameter: pH

The equation below gives the relationship between pH and hydrogen ion concentration in mol mL^{-1} :

$H^{+} = 10^{-pH}$

Water with a hydrogen ion concentration of 10^{-6} mol L^{-1} or 10^{-4} g L^{-1} has, for instance, a pH value of 6.

Because of the hydrogen transportation by NAD, different products of fermentation are developed: the H^{+} ions isolated from the substrate are carried over to the uncharged NAD. The NAD molecules so charged ($NADH+H^{+}$) regenerate (oxidize), by forming H_2 molecules:

$$NADH + H^{+} \rightarrow H_2 + NAD^{+} \Delta G^{o} = +18.07 kJmol^{-1}$$

This reaction occurs independently of the hydrolysis and acidification of hydrocarbon and proteins. Hydrocarbons are easier to acidify, and no pH-buffering ions are released as with the degradation of proteins. Therefore the pH value decreases more easily. With the degradation of carbohydrates, the partial pressure of hydrogen increases more easily, as with other substances. This happens in combination with the formation of reduced acidic intermediate products.

Even when the hydrolysis and the acidification occur in different aparatuses and are separated from the methanation, complete suppression of the methanation is almost impossible.

The pH optimum of the methane-forming microorganism is at pH = 6.7–7.5. Therefore, it is important to adjust the pH - value in the second stage higher than that in the first stage of a two-stage biogas plant. Only Methanosarcina is able to withstand lower pH values (pH = 6.5 and below). With the other bacteria, the metabolism is considerably suppressed at pH <6.7.

If the pH value sinks below pH = 6.5, then the production of organic acids leads to a further decrease of the pH value by the hydrolytic bacteria and possibly to cessation of the fermentation. In the reality, the pH-value is held within the neutral range by natural procedures in the fermenter. Two buffering systems ensure this.

A too strong acidification is avoided by the carbon dioxide/hydrogen carbonate /carbonate buffer system. During the fermentation, CO_2 is continuously evolved and escapes into air. With falling pH value, more CO_2 is dissolved in the substrate as uncharged molecules. With rising pH value, the dissolved CO_2 forms carbonic acid, which ionizes. Thus, hydrogen ions are liberated.

$$CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + 2CO_3^{2-}$$

At pH = 4 all CO_2 is as free molecules; at pH = 13 all CO_2 is dissolved in the form of carbonate in the substrate. The center around which the pH value swings with this system is at pH = 6.5. At a concentration of 2.5–5 g L^{-1}, hydrogen carbonate gives particularly strong buffering.

A too weak acidification is avoided by the ammonia - ammonium buffer system (Figure 15). With falling pH value, ammonium ions are formed with release of hydroxyl ions. With rising pH value, more free ammonia molecules are formed.

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

$$NH_3 + H^+ \leftrightarrow NH_4^+$$

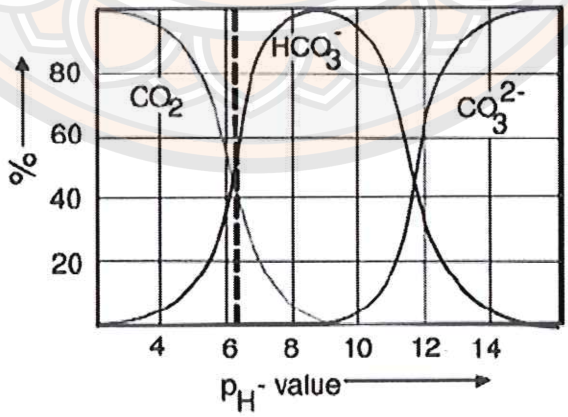

Figure 15 Ammonia-ammonium buffer system

Source: Dieter Deublein and Angelika Steinhauser, 2010

The center, around which the pH value swings with this system, is at pH = 10.

Both buffering systems can be overloaded by a feed of particularly rapidly acidifying waste water or organic material, by toxic substances, by a decrease in temperature, or by a too high volume load in the bioreactor; e.g., by feeding waste water out of a starch processing plant, which incurs the possibility of acetic acid toxification. Consequences are:

1. increase in the amount of uncharged fatty acid molecules–this leads sometimes to increase in the hydrogen content in the substrate and CH_4 production, sometimes to the detriment of the methanation
2. inhibition of the methanation by increase in the proportion of unhydrolyzed inhibitors, e.g., sulfide
3. rise of the pH value due to degradation from sulfate to H_2S
4. inhibition of reactions by rise in the proportion of free ammonia.

A drop in the pH-value and a rise of the CO_2 in the biogas is an indication of a disturbance of the fermentation process. A first sign of the acidification is the rise of the propionic acid concentration. Measures for the prevention of excessive acidification are:

5. Stoppage of the substrate supply, so that the methanogenic bacteria are able to degrade the acid
6. Reduction of the organic space load (increase of the residence time)
7. Increase of the buffering potential of the substrate by addition of selected co-substrates, in particular if the buffering potential of the substrate is small. It must be taken into consideration that the buffering potential changes because of the removal of the CO_2
8. Continuous removal of the acids
9. Addition of neutralizing substances: milk of lime (CaO, $Ca(OH)_2$), sodium carbonate (Na_2CO_3), caustic soda solution ($NaOH$)
10. Addition of diluting water
11. Emptying and restarting the fermenter.

As a result of the feed of special caustic solutions for adjusting the pH-value or of the addition of cleaning and disinfecting agents, values of pH >10 can arise in the reactor, which will lead to an irreversible loss of the activity of the bacteria. Cleaning and disinfecting agents should therefore be tested for their inhibiting potential before their first application in the plant.

Parameter: redox potential

In the bioreactor, low redox potentials are necessary; e.g. monocultures of methanogenics need between −300 and −330 mV as an optimum. In addition, the redox potential can also rise to 0 mVs in the fermenter. In order to keep a low redox potential, few oxidizing agents should be supplied, e.g., no oxygen, sulfates, nitrates, or nitrites.

Parameter: nutrients (C/N/P-ratio)

The C/N-ratio of the substrate should be in the range of 16: 1– 25: 1 (Table 5). But this is only an indication, because nitrogen can also be bound in lignin structures.

The need for nutrients is very low due to the fact that with the anaerobic process not much biomass is developed, so that for methane formation even a nutrient ratio C : N : P : S of 500–1000 : 15–20 : 5 : 3 and/or an organic matter ratio of COD : N : P : S = 800 : 5 : 1 : 0.5 is sufficient.

Substrates with a too low C/N ratio lead to increased ammonia production and inhibition of methane production. A too high C/N ratio means lack of nitrogen, from which negative consequences for protein formation and thus the energy and structural material metabolism of the microorganisms result. A balanced composition is absolutely necessary; e.g. the mixture of rice straw and latrine waste as usual in China of the co-fermentation of elephant dung with human waste as done in Nepal.

Table 5 C/N ratio of organic wastes

Waste	DM content	Organic substances % of DM	C/N ratio
Straw	ca. 70	90	90
Waste from sawmills	20–80	95	511
Paper	85–95	75	173
Waste from housholds	40–60	40	18
Sewage sludge	0.5–5	60	6

Parameter: trace elements

For survival, microorganisms need certain minimum concentrations of trace elements Fe, Co, Ni, Se, W, and Mg.

Parameter: precipitants (calcium carbonate, MAP, apatite)

At abt. 100 mg L^{-1} Ca^{2+}, calcium carbonate ($CaCO_3$) begins to precipitate from aqueous suspensions. At concentrations up to 150 mg L^{-1} Ca^{2+}, the formation of readily–sedimenting sludge flakes (pellets) is promoted.

When the calcium carbonate concentration exceeds 500 mg L^{-1} Ca^{2+}, on the one hand (positively) the formation of biofilms and biomass growth is supported, but on the other hand (negatively), some types of bioreactors can be overgrown too fast and blocked by lime deposits.

With calcium concentrations of over 1000 mg L^{-1}, as they occur, e.g., in the German sugar industry, separation of the lime is recommended, e.g., in a hydrocyclone or a sedimentation apparatus or with the aid of carriers, which can than be cleaned from the lime residues and fed back into the reactor.

In the paper and milk industries, various phosphate compounds precipitate, e.g., apatite, because of the higher Ca concentrations (400–1000 mg L^{-1} Ca^{2+}) and the high concentrations of phosphoric compounds (40–100 mg L^{-1}P). In order to avoid calcium carbonate linings, permanent magnets are used.

Magnesium ammonium phosphate (MAP), struvite ($MgNH_4$ $PO_4.6H_2O$) precipitates if the three components in combination are present together, e.g. with waste water from the wheat and potato industry. MAP precipitates mainly by turbulent flow as in pumps or by exceeding a certain pH value, depending on the waste water, frequently starting at pH = 7 and temperatures >30°C.

Parameter: biogas removal

The removal of the produced gases (methane, carbon dioxide, hydrogen sulfide) from the substrate has a considerable influence on the biological reactions. The attainable microorganism concentration can be increased by a factor of 12 in the case of extremely thermophilic methanogenics when produced gases are removed to a sufficient extent.

In particular, the degassing behavior of the substrate plays a tremendous role whenever the produced gases inhibit the metabolism.

The material transfer from the liquid phase into the gaseous phase can be effected by technical means. By feeding back the produced biogas into the reaction system, the $k_L.a^*$ value, characteristic of the material transfer between liquid and gaseous phase, can be increased by 50% and the inhibition of the microorganisms by H_2S can be reduced.

* Material transfer number $k_L.a$ = product of material transfer coefficient k_L and surface a

Parameter: inhibitors

When planning and operating a biogas plant, it has to be borne in mind that some compounds which are formed, even to a limited extent, as products of the metabolism of the anaerobic disgradation, inhibit the biocenosis and can even be toxic at higher concentrations (Figure 16)

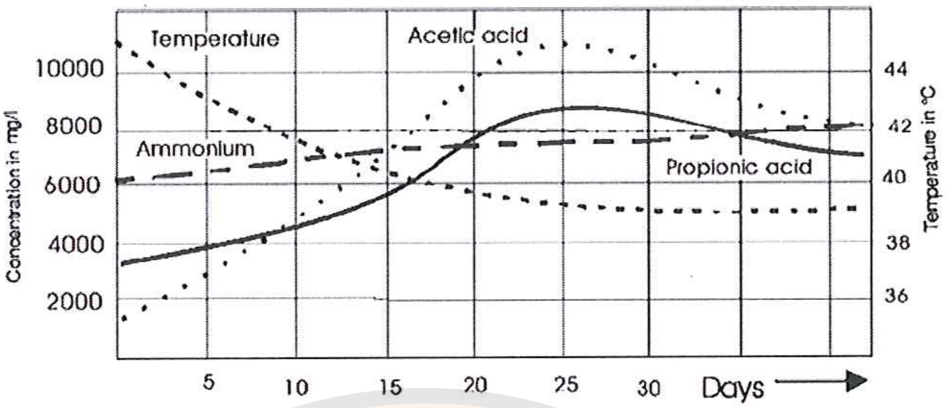

Figure 16 Progression of an inhibition

Source: Dieter Deublein and Angelika Steinhauser, 2010

The inhibition depends on the concentration of the inhibitors, the composition of the substrate, and the adaptation of the bacteria to the inhibitor. Anaerobic bacteria need a low concentration of the inhibitors as trace elements. They degrade a high percentage of the inhibitor.

About inhibitors and their effect on the anaerobic process, many and sometimes very contradictory comments have been published. This is because

1. microorganisms adapt to their environment. How quickly the adaptation takes place depends on the composition of the biocenosis.

2. inhibitors have different effects, depending upon whether they flow intermittently or continuously. In the case of a single brief addition, irreversible damage develops only if the exposure time is too long and the concentrations are too high.

3. the inhibitors are not able to penetrate very fast into the biofilm if fermenters with retained biomass are used in preference to conventional fermenters with lower biomass concentration or immobilized biomass.

4. the effect of different inhibitors is affected by other components; thus, for example, the restraining effect of heavy metals is affected by any anions present at the same time, since metals can be precipitated, e.g., by hydrogen sulfide, or can be bound in complexes. On the other hand, a too high sulfide ion concentration can even have a toxic effect–depending upon temperature and pH value. The reduction of a pollutant

by addition of a material working against it can therefore be problematical because of different interactions.

Usually, however, anaerobic processes seem to be relatively insensitive to inhibitors and mostly adaptable, even to concentrations that are toxic under other circumstances.

Oxygen

The majority of the acidifying bacteria are facultatively anaerobic, so that the exclusion of oxygen is not absolutely necessary for acidification. But methanogenics are obligatorily anaerobic–the inhibition begins at 0.1 mg L^{-1} O_2 . They take nitrate, sulfate, or carbonate as the oxygen replacement, i.e. as the hydrogen acceptor.

Since under operational conditions the methanogenics always grow in the presence of facultatively anaerobic acidifying bacteria, which consume available oxygen immediately, anaerobic conditions can be maintained in closed reactors. The small amount of air, which is injected frequently for the biotechnological desulfurization of the biogas, usually has no inhibiting effect on the methane formation.

Sulfur compounds

Wastes and industrial waste water can contain a high concentration of sulfur compounds, e.g., waste water from the production of yeast, viscose rayon, cartons, citric acid, or fiber board. Sulfur compounds can be present

1. as sulfate (in industrial waste water in high concentrations)
2. as sulfide
3. as hydrogen sulfide in the gas
4. as undissociated hydrogen sulfide in the liquid, and (toxically)
5. in dissociated form HS^-, S^-.

Sulfate can be problematical, because H_2S develops from it in a stage before methane formation. H_2S can be inhibiting to the process.

$$SO_4^{2-} + 4H_2 \rightarrow H_2S + 2H_2O + 2OH^-$$

$$SO_4^{2-} + CH_3COOH \rightarrow H_2S + 2HCO_3^-$$

Sulfate can also inhibite the methane formation, because sulfate-degrading microorganisms are dominant as they need less energy and/or do not need a symbiosis partner: for sulfate degradation, a free energy of -154 kJ mol^{-1} and/or -43 kJ mol^{-1} is needed, while for the methanation of carbon dioxide and hydrogen or acetic acid only -135.4 kJ mol^{-1} and/or -30.9 kJ mol^{-1} is needed.

Dissolved sulfide in the waste water up to 50 mg L^{-1} does not lead to problems for methane formation if the pH is less than 6.8 in the bioreactor. Microorganisms can adapt themselves to sulfide and can survive at up to 600 mg L^{-1} Na_2S and 1000 mg L^{-1} H_2S.

H_2S develops as by-product with nearly all substrates. It escapes with the biogas and is dissolved in undissociated and dissociated form in the substrate as a weak acid, whereby hydrogen sulfide ions and sulfide ions develop.

$$H_2S \leftrightarrow HS^- + H^+ \leftrightarrow S^{2-} + 2H^+$$

The chemical equilibrium between the undissociated and dissociated form depends on the pH value (Figure 17).

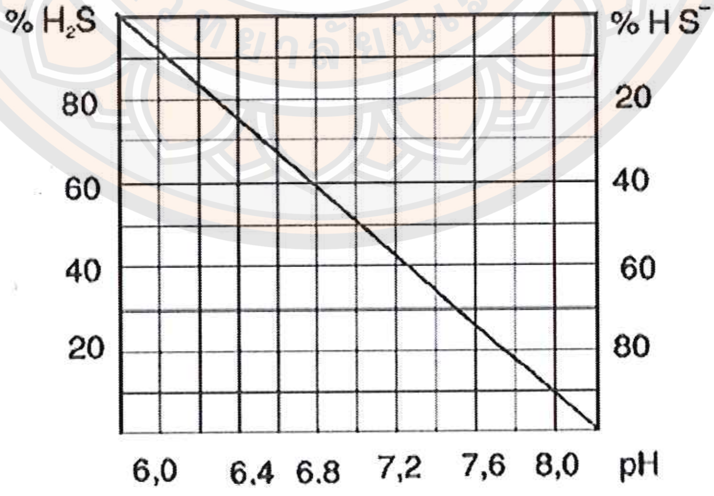

Figure 17 Dissociation of hydrogen sulfide

Source: Dieter Deublein and Angelika Steinhauser, 2010

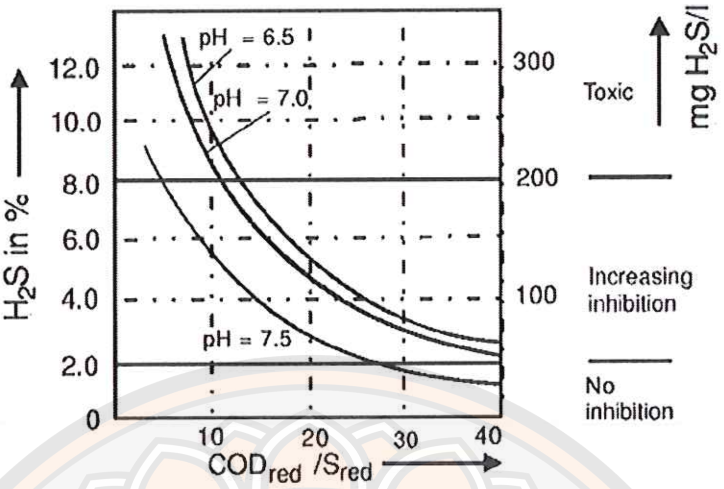

Figure 18 **Inhibition through hydrogen sulfide at 30% CO_2, 38°C, 10 g/L, organic matter as COD_{red}**

Source: Dieter Deublein and Angelika Steinhauser, 2010

With decreasing pH value, the proportion of dissolved undissociated hydrogen sulfide rises. In dissolved form it works directly as cellular poison even at a concentration of ca. 50 mg L^{-1} (Figure 6.18). Above that, H_2S can cause process inhibition indirectly by the precipitation of essential trace elements as insoluble sulfides.

With organic matter as COD >100, basically no problems are to be expected through H_2S. With organic matter as COD <15, methane production is possible only in special cases. However, the temperature is also important: with rising temperature the toxicity of hydrogen sulfide increases.

In some cases, hydrogen sulfide in the substrate is favorable, particularly if the substrate contains heavy metal ions at a level at which they must be precipitated.

Continuous monitoring of the H_2S content of the biogas is recommended. An unexpected rise should be dealt with by

1. increasing the pH value by addition of caustic soda
2. admitting iron salt, which works as an H_2S scavenger
3. lowering the volume load.

When high sulfur content in the waste water is to be expected, a two–stage process should be prefered, so that the removal of the sulfur compounds can be achieved in the first stage.

Organic acids (fatty acids and amino acids)

Normally, organic acids are present in the substrate. These are decomposed during methanation. They exist partly in the undissociated and partly in the dissociated form (Figure 20). Especially undissociated acids have an inhibiting effect, because they penetrate as lipophilics into cells, where they denaturate the cell proteins.

If too much organic acid is fed to the bioreactor within a short time and/or their degradation is hindered, a too strong acidification takes place. Therefore the load of the methane reactor may be increased only very slowly, fermenting easily acidifiable substrates or ensilaged energy plants in particular.

The inhibiting effect is additionally intensified by the drop in the pH-value (Figure 6.20). At pH <7, the inhibiting threshold is up to 1000 mg L^{-1} acetic acid. For iso-butyric acid or iso-valeric acid, the inhibiting threshold can be as low as a concentration of 50 mg L^{-1} undissociated fatty acid without adaptation. Propionic acid is strongly inhibiting even at a concentration of 5 mg L^{-1} (corresponding to ca. 700 mg L^{-1} undissociated acid at pH = 7).

Aromatic amino acids probably lead to inhibition, e.g., with waste water from potato processing (Table 6).

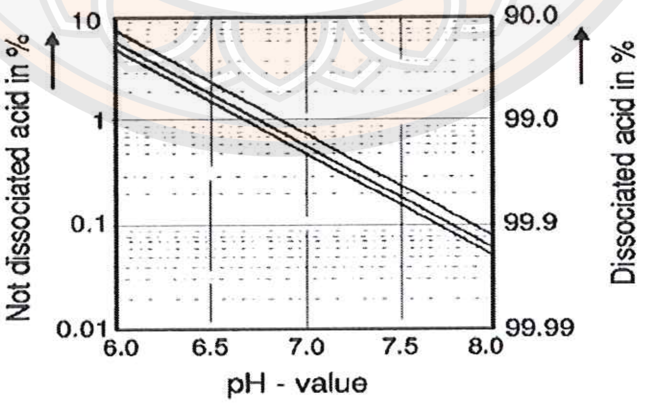

Figure 19 Dissociated and not dissociated acid

Source: Dieter Deublein and Angelika Steinhauser, 2010

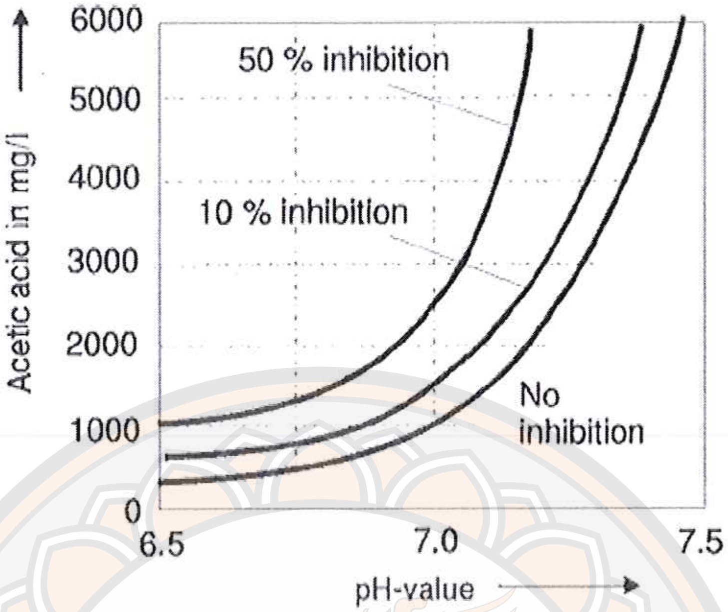

Figure 20 Inhibition through acetic acid

Source: Dieter Deublein and Angelika Steinhauser, 2010

Table 6 Limits for sulfur compounds and fatty acids

Substance	Minimum amount required as trace element [mg L^{-1}]	Concentration at which inhibition starts [mg L^{-1}]	Toxicicity [mg L^{-1}] for adopted MO
Sulfur compounds	Organic matter as COD : S ratio at 800 : 0.5	H_2S: 50 S: 100 Na_2S: 150	1000 600
Iso-Butyric acid	n.a.	50	n.a.
Long-chain fatty acids	n.a.	1.2 mM C12 and C18	n.a.
Petrochemical products	n.a.	0.1 mM hydrocarbonates, aromatic halogenic products	n.a.

Nitrate (NO_3^-)

Nitrate is denitrified in the first stage of decomposition, in any case before the methanation. Inhibition of the methanation is only possible with substrates with high nitrate content NO_3-N >50 mg Mg^{-1}. This is the case if the denitrification does not work properly. Therefore, before nitrate - rich sludges can be fermented, the oxygen bound in the nitrate/nitrite must be split off, e.g., in a denitrification stage. On denitrification in the anaerobic reactor,

1. the redox-potential becomes more negative, in favoring the anaerobic process.
2. the gas quality decreases because of the higher nitrogen content of the biogas.
3. carbon is consumed and is no longer available for methanation, which is noticeable in the output of the plant.

Ammonium (NH_4^+) and ammonia (NH_3)

Ammonia and ammonium result from the anaerobic biological degradation of nitrogen compounds. Ammonia forms ammonium ions in the substrate, the extent of this depending on the pH value. Ammonia has an inhibiting effect, and with larger concentrations can even be toxic, while ammonium is innocuous. It can only have an inhibiting effect at concentrations NH_4^+-N >1500 mg Mg^{-1}, where its inhibiting effect is predominantly due to the species whose concentration depends on the pH value. Ammonium leads to potassium loss of methanogenic microorganisms and can show reciprocal effects with Ca^{2+} or Na^+.

The inhibition by ammonium increases with rising pH value (Figure 21) at constant concentration: e.g., the ratio ammonium to ammonia is 99 : 1 at pH = 7, and 70 : 30 at pH = 9. Often, even small pH value variations are sufficient to affect the inhibiting effect.

The equilibrium between ammonium and the inhibiting ammonia (Table 7) is temperature-dependent: with rising temperature the equilibrium between NH_4 and NH_3 is shifted in favor of NH_3, so that the inhibition increases with rising temperature.

In communal plants, waste water from the anaerobic plant is recycled to the denitrification tank of the sewage treatment plant. It has to be borne in mind that the ratio of organic matter (as COD) to nitrogen content should be at 5–6: 1 and has often to be adjusted by adding raw waste water to the waste water from the anaerobic plant.

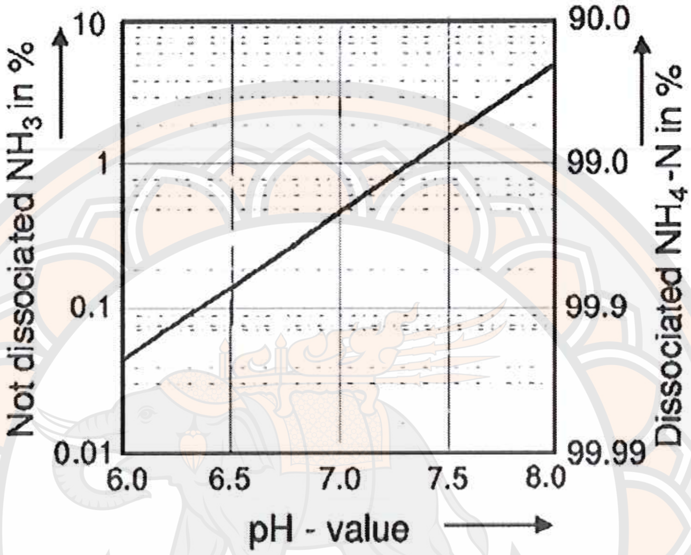

Figure 21 Dissociated and not dissociated ammonium

Source: Dieter Deublein and Angelika Steinhauser, 2010

Table 7 Limit values of ammonium and ammonia

Substance	**Regulation/interaction with**	**Concentration at which inhibition starts [mg/L]**	**Toxicicity [mg/L] for adopted MO**
Ammonium	Ca^{2+}, Na^{+}	1,500–10,000	30,000
Ammonia	–	80	150

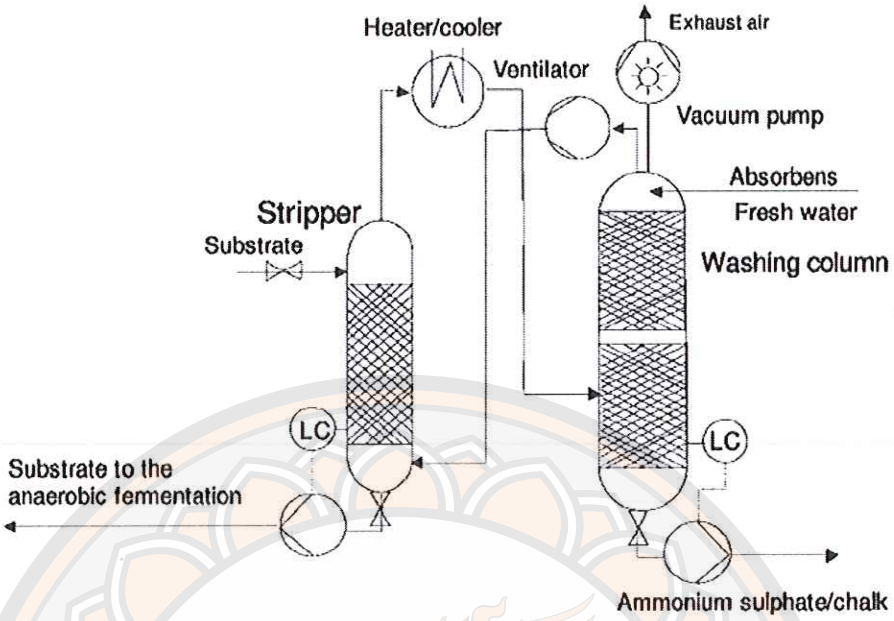

Figure 22 ANAStrip-process

Source: Dieter Deublein and Angelika Steinhauser, 2010

Ammonia can be removed from the substrate by the ANAStrip-process, system GNS (Figure 22).

The plant is operated with a circulated gas. The circulated gas ascends in the substrate in the stripper at 80°C (max.) and low vacuum and leaves the stripper ammonia - enriched. The circulated gas then flows through a scrubber in which ammonia reacts with an absorbent (REA gypsum) in aqueous solution with formation of ammonium sulfate and lime fertilizer.

$$CaSO_4 + 2NH_3 + CO_2 + H_2O \rightarrow CaCO_3 + (NH_4)_2SO_4$$

The ammonium sulfate salt is very water soluble and can be taken off as 40% fertilizer concentrate solution from the scrubber. The ammonia - free circulated gas from the scrubber is injected again into the stripper by a blower. Within 2 h, the circulated gas takes off at least 70% of the bound nitrogen of the substrate. The special advantages of the procedure are:

1. no consumption of caustic soda solution or other alkalis to extract ammonia from the liquid manure
2. no neutralization of the liquid manure necessary after stripping
3. no increase of the salt concentration in the liquid manure
4. low operating temperature (80°C max.) when stripping, as the waste heat supply can be used
5. no need for stripping steam, since the procedure works under low vacuum
6. minimum water distillation when stripping, because the process works without steam injection. The fertilizer from the plant does not become dehydrated.
7. direct formation of ammonium sulfate from the vaporized ammonia without formation of concentrated ammonium solution as intermediate
8. no odors from the concentrated ammonia solution possible
9. no expensive safety devices necessary for the storage and dosage of ammonia solution, caustic soda solution, and sulfuric acid
10. no environmental pollution or danger to personnel from aggressive chemicals

Heavy metals

Heavy metals, which act as trace elements at low concentrations stimulating the activity of the bacteria, can have toxic effects at higher concentrations (Table 8). In particular lead, cadmium, copper, zinc, nickel, and chromium can lead to disturbances in biogas plants, but so also can sodium, potassium, calcium, and magnesium.

The content of lead, cadmium, chromium, copper, nickel, mercury, and zinc in the biomass rises during fermentation, but only slightly. The high zinc contents of the pig liquid manure originate from the piglet fodder, which often contains a zinc additive as an antibiotic.

Heavy metals can be bound or precipitated by 1–2 mg L^{-1} sulfides. Copper, cadmium, lead, and zinc can be eliminated by polyphosphates (complexing agents). They are then no longer biologically available.

Tannins

Condensed tannins – secondary plant compounds which are to be found in many legumes–can specifically and dose - dependently inhibit methane formation. Data on the inhibiting threshold are not available.

Table 8 Inhibiting or toxic concentrations of different metals in solution in the reactor. The inhibition depends on whether the metals are there as ions or as carbonates

Substances	**Minimum amount required as trace element [mg/L]**	**Parameters affected**	**Concentration at which inhibition starts [mg/L]**		**Toxicity [mg/L] for adopted MO**
			Free ions	**As carbonate**	
Cr	0.005–50	–	28–300	530	500
Fe	1–10	–	n.a.	1750	n.a.
Ni	0.005–0.5	–	10–300		30–1000
Cu	Essentially with acetogenic MO	–	5–300	170	170–300
Zn	Essentially with acetogenic MO	–	3–400	160	250–600
Cd	n.a.	–	70–600	180	20–600
Pb	0.02–200	–	8–340	n.a.	340
Na	n.a.	pH–Wert	5,000–30,000	n.a.	60,000
K	n.a.	Osmosis of the methane formers	2,500–5,000	n.a.	n.a.
Ca	n.a.	Long–chain fatty acids	2,500–7,000	n.a.	n.a.

Table 8 (cont.)

Substances	**Minimum amount required as trace element [mg/L]**	**Parameters affected**	**Concentration at which inhibition starts [mg/L]**		**Toxicicity [mg/L] for adopted MO**
			Free ions	**As carbonate**	
Mg	Essentially with acetogenic MO	Fatty acids	1,000–2,400	n.a.	n.a.
Co	0.06	–	n.a.	n.a.	n.a.
Mo	0.05	–	n.a.	n.a.	n.a.
Se	0.008	–	n.a.	n.a.	n.a.
Mn	0.005–50	–	1,500	n.a.	n.a.
HCN	0.0	–	5–30	n.a.	n.a.
C_6H_6O	Inhibiting until the microrganisms are adapted. Then it is completely degraded.				

Other inhibiting thresholds

Disinfectants (hospitals, industry), herbicides, and insecticides (agriculture, market gardens, households), surfactants (households), and antibiotics can often flow with the substrate into the methanation and can there cause nonspecific inhibition (Table 9).

Chlorinated hydrocarbons such as chloroform at levels above 40 mg L^{-1} and/or chlorinated fluorocarbons also have toxic effects. The swelling concentration, starting from which an inhibition begins, depends frequently on the time of adaptation during which the bacteria are exposed to the inhibitor. Usually the inhibition decreases with increasing time of adaptation. Therefore, sudden changes of concentration of inhibitor have to be avoided.

Table 9 Inhibiting or toxic concentrations of different inhibitors

Substance	Concentration at which inhibition starts [mg/L]	Toxicity [mg/L] for adapted MO
Chloroform	40	n.a.
Chlorofluorohydrocarbons etc.	50	n.a.
Formaldehyde	100	1,200
Ethene and terpenes	1–50	n.a.
Disinfectants and antibiotics	1–100 (not necessarily)	n.a.

Parameter: degree of decomposition

Complete degradation of the organic dry matter is theorically only possible if no lignin from wood-containing biomasses is present. The normal degree of decomposition varies within the range 27–76% and is usually abt. 43.5%.

Operational parameters

Organic load

The construction and operation of a biogas plant is a combination of economical and technical considerations. Obtaining the maximum biogas yield, by complete digestion of the substrate, would require a long retention time of the substrate inside the digester and a correspondingly large digester size. In practice, the choice of system design (digester size and type) or of applicable retention time is always based on a compromise between getting the highest possible biogas yield and having justifiable plant economy. In this respect, the organic load is an important operational parameter, which indicates how much organic dry matter can be fed into the digester, per volume and time unit, according to the equation below:

$$B_R = m*c/V_R$$

where	B_R	organic load [kg/d*m³]
	m	mass of substrate fed per time unit [kg/d]
	c	concentration of organic matter [%]
	V_R	digester volume [m³]

Hydraulic retention time (HRT)

An important parameter for dimensioning the biogas digester is the hydraulic retention time (HRT). The HRT is the average time interval when the substrate is kept inside the digester tank. HRT is correlated to the digester volume and the volume of substrate fed per time unit, according to the following equation

$$HRT = V_R/V$$

Where	HRT	hydraulic retention time [days]
	V_R	digester volume [m³]
	V	volume of substrate fed per time unit [m³/d]

According to the above equation, increasing the organic load reduces the HRT. The retention time must be sufficiently long to ensure that the amount of microorganisms removed with the effluent (digestate) is not higher than the amount of reproduced microorganisms. The duplication rate of anaerobic bacteria is usually 10 days or more. A short HRT provides a good substrate flow rate, but a lower gas yield. It is therefore important to adapt the HRT to the specific decomposition rate of the used substrates. Knowing the targeted HRT, the daily feedstock input and the decomposition rate of the substrate, it is possible to calculate the necessary digester volume.

Parameter list

A number of parameters (Table 10) can be used for evaluation of biogas plants and for comparing different systems.

In literature two main categories of parameters can be found:

1. Operating data, which can be determined by measurement?
2. Parameters, which can be calculated from the measured data

In order to evaluate the performance capabilities of a biogas plant a multi-criteria analysis should be performed. Evaluations based on a single parameter can never do justice to the process. In order to determine if a biogas plant can provide a return on investment, in an acceptable time frame, economic parameters must always be included.

Table 10 Operational parameters of biogas plants

Parameter	Symbol	Unit	Determination
Temperature	T	^oC	Measurement during operation
Operational pressure	P	Mbar	Measurement during operation
Capacity, throughput	V	m^3/d; t/d	Measurement
Reactor volume	V_R	m^3	Determined by construction
Gas quantity	V per day V per year	m^3/d; m^3/a	Measurement during operation and conversion to Nm^3
Retention time (hydraulic, minimum guaranteed)	HRT MGRT	d	Calculation from operating data
Organic load		kg oTS/ (m^3*d)	Calculation from operating data
Methane concentration in biogas	CH_4	%	Measurement during operation
Specific biogas yield		%	Calculation from operating data

Table 10 (cont.)

Parameter	Symbol	Unit	Determination
Specific biogas production		m^3/m^3	Calculation from operating data
Gross energy		kWh	Determination from the quantity of biogas and methane concentration
Electricity production		kWh	Measurement at the BTTP generator
Output to grid		kWh	Measurement after the BTTP generator
Efficiency of BTTP	η	%	Calculation from operating data
Station supply thermal/ electric		kWh	Basis of planning, afterwards measurement during operation
Specific station supply thermal/ electric		kWh/m^3 Input kWh/GV	Calculation from operating data
Energy production		kWh	Sum of energy that can be sensibly utilized. Calculation from operating data
Plant efficiency	η	%	Net energy drawn from gross energy
Availability		%	Percentage of hours in a year in which a plant is fully functioning
Utilization		%	Ratio of the real quantity input to the projected capacity
Total investment		€	All expenses caused by the biogas plant

Table 10 (cont.)

Parameter	Symbol	Unit	Determination
Subsidies		€	Pre-determined
Subsidy percentage		%	Percentage of all subsidies in relation to total investments
Specific investments			Only sensible when primarily manure from animal husbandry is used
Specific treatment costs			Calculation

Digester Types

Processes that are not Appropriate for Digesting Manure

A variety of high rate anaerobic processes, which retain bacteria have been developed to treat soluble organic industrial wastes. These "high rate" digesters have reduced hydraulic detention times from 20 days to a few hours. They include anaerobic filters, both up-flow and down-flow, and a variety of biofilm processes such as fixed film packed bed reactors. Bacteria are retained in these reactors as films on carriers such as plastic beads, or sand, or on support media of all configurations. The waste washes past the retained bacteria. The bacteria convert the soluble constituents to gas but have little opportunity to hydrolyze and degrade the particulate solids, unless the solids become attached to the biomass.

These reactors are not suitable for digesting waste since they are not effective in converting particulate solids to gas and tend to clog while digesting manure slurries. These high rate reactors can treat the soluble component of waste. But only a fraction of the available energy will be recovered.

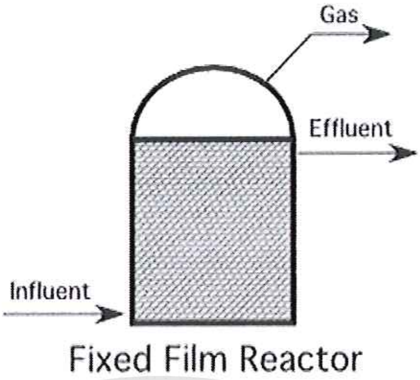

Figure 23 Packed Fixed Film Reactor

Source: Burke D.A., (2001)

A widely used industrial waste anaerobic digester is the UASB or "Up-flow Anaerobic Sludge Blanket", reactor. The process stores the anaerobic consortia as pellets, approximately the size of a pea. The up-flow anaerobic sludge blanket reactor (UASB) is widely used in industrial treatment processes throughout the world. It is an extremely effective process for converting soluble organic materials, such as sugar to methane gas. It has not been used for processing waste since it is ineffective in converting solids to gas. It is primarily used to convert non-particulate or soluble waste to gas.

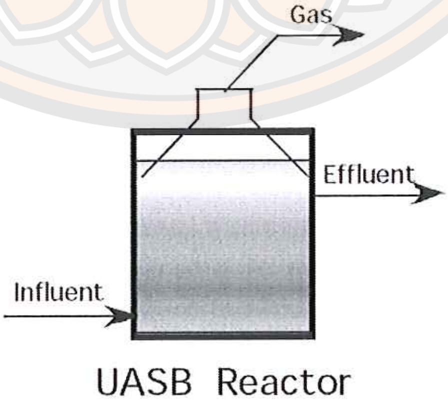

Figure 24 Up-flow Anaerobic Sludge Blanket Reactor

Source: Burke D.A., 2001

The anaerobic baffled reactor is a horizontal version of the up-flow anaerobic sludge blanket reactor. Both store large quantities of anaerobic bacteria as pellets approximately the size of a pea. Unfortunately, these very successful anaerobic reactors are not effective in digesting particulate waste.

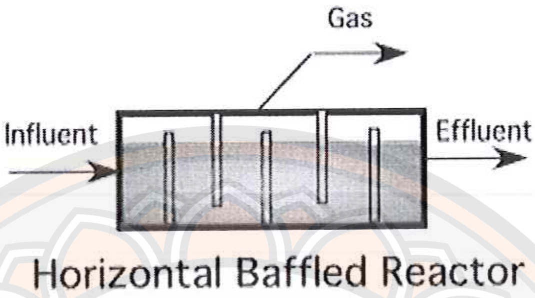

Figure 25 Baffled Reactor

Source: Burke D.A., 2001

Particulate solids tend to settle in the horizontal baffled reactor (HBR) while organic fibers will form a mat on the surface. There are no known instances of the HBR being used for the treatment of waste. Unless the waste was thoroughly screened and all particulate matter removed the HBR would tend to become clogged. The removal of solids by screening and gravity sedimentation will eliminate up to 80% of the energy generating potential from dairy waste.

Processes that can be used for Digesting Manure

The processes that have been used for digesting waste can be subdivided into high rate and low rate processes. Low rate processes consist of covered anaerobic lagoons, plug flow digesters, and mesophilic completely mixed digesters. High rate reactors include the thermophilic completely mixed digesters, anaerobic contact digesters, and hybrid contact/fixed film reactors.

Anaerobic Lagoons (Very Low Rate)

Anaerobic lagoons are covered ponds. Manure enters at one end and the effluent is removed at the other. The lagoons operate at psychrophilic, or ground temperatures. Consequently, the reaction rate is affected by seasonal variations in temperature.

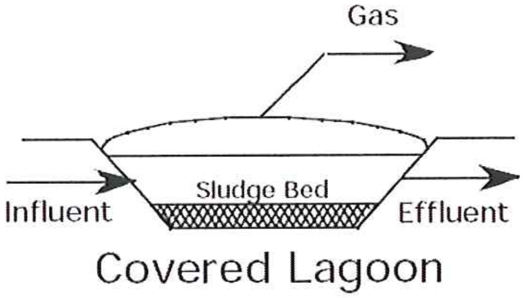

Figure 26 Anaerobic Lagoons

Source: Burke D.A., 2001

Since the reaction temperature is quite low, the rate of conversion of solids to gas is also low. In addition, solids tend to settle to the bottom where decomposition occurs in a sludge bed. Little contact of bacteria with the bulk liquid occurs. The biomass concentration is low, resulting in very low solids conversion to gas (High F/M ratio with poor growth rates at low temperatures). Little or no mixing occurs. Consequently, lagoon utilization is poor. Anaerobic lagoons have been used to treat parlor and free stall flush water. Gas production rates have been low and seasonal. Solids may be screened and removed prior to entering the lagoon. A considerable amount of energy potential is lost with the removal of particulate solids. The advantage of anaerobic lagoons is the low cost. The low cost is offset by the lower energy production and poor effluent quality. Periodically the covered lagoons must be cleaned at considerable cost. Nuisance odors may be generated while cleaning the lagoons.

Completely Mixed Digesters (Low Rate)

The most common form of an anaerobic digester is the completely mixed reactor. Most sewage treatment plants and many industrial treatment plants use a completely mixed reactor to convert waste to gas. The completely mixed reactor is a tank that is heated and mixed.

Most completely mixed reactors operate in the mesophilic range. All of the initial anaerobic digesters used to treat manure were completely mixed mesophilic digesters. The cost of mixing is high, especially if sand, silt, and floating materials, present in the waste stream, must be suspended throughout the digestion period.

Some completely mixed reactors operate in a thermophilic range where sufficient energy is available to heat to reactor. Highly concentrated readily degradable waste is required in order to generate sufficient heat for the thermophilic range of operation. Completely mixed thermophilic digesters are used in the EEC to treat animal manure (Ahring, Ibrahim, et al., 2001). Recently, completely mixed thermophilic digesters were proposed in Oregon to treat dairy manure (Tillamook, 1999).

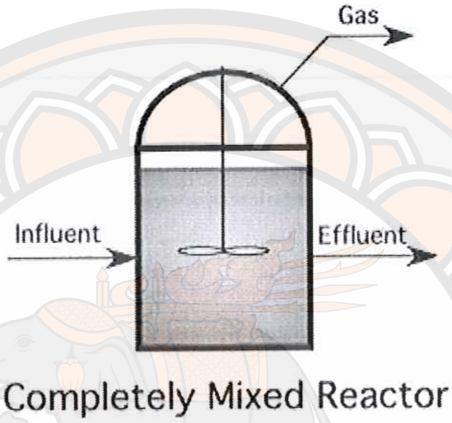

Figure 27 Completely Mixed Reactor

Source: Burke D.A., 2001

Most completely mixed reactors are heated with spiral flow heat exchangers. These heat exchangers apply hot water to one side of the spiral and the anaerobic slurry to the other. The spiral heat exchangers have proven to be a successful method of efficiently transferring heat.

Completely mixed reactors can be constructed of a variety of materials. In the U.S. most completely mixed reactors have a low profile with a diameter greater than the height. Some municipal digesters in the U.S. and most in Europe have an egg shape with a height much greater than the diameter. The egg shape enhances mixing while eliminating much of the stratification.

Completely mixed reactors can have fixed covers, floating covers, or gas holding covers. Most municipal digesters have floating covers. Floating covers are more expensive than fixed covers.

Mixing can be accomplished with a variety of gas mixers, mechanical mixers, and draft tubes with mechanical mixers or simply recirculation pumps. The most efficient mixing device in terms of power consumed per gallon mixed is the mechanical mixer. Most municipal digesters are intensely mixed to reduce the natural stratification that occurs in a low profile tank. A large amount of evidence has been accumulated over the past 10 years indicating that intense mixing may inhibit the bacterial consortia. But, intense mixing is required to keep sands and silts in suspension.

The advantage of the completely mixed reactor is that it is a proven technology that achieves reasonable conversion of solids to gas. It can be applied to the treatment of slurry waste such as manure (Ecotope, 1979). The disadvantage of the completely mixed reactor is the high cost of installation, and the energy cost associated with mixing the digester. The completely mixed conventional anaerobic digester is a biomass growth based system. The process requires a constant conversion of a portion of the feed solids to anaerobic bacteria rather than gas. Since anaerobic bacteria are constantly wasted from the process, new bacteria must be produced to replace the lost bacteria. If the bacteria are retained, the portion of the waste that would have been converted to new bacterial cells will be converted to gas. For this reason, bacterial growth based systems are not as efficient as retained biomass systems.

The advantage of the completely mixed thermophilic reactor is the rapid conversion of solids to gas and biomass (Ratkowsky, Olley, et al., 1981). Some claim that the rate of conversion is three times greater with thermophilic reactors. Consequently, the HRT can be lower and the gas production greater. The disadvantage of the thermophilic reactor is the energy required to heat cold dairy manure to thermophilic temperatures. Additional costs are incurred in tank insulation and heat exchangers. Sufficient heat may not be available from the gas produced unless the solids are highly concentrated. Thermophilic digestion of manure cannot be used with manure diluted with parlor or flush water since sufficient energy will not be available to meet the heat requirements. In addition, the higher temperature thermophilic reactors increase end product inhibition, especially ammonia and organic acids (Ahring, Ibrahim, et al., 2001).

Plug Flow Digesters (Low Rate)

The plug flow anaerobic digester is the simplest form of anaerobic digestion (Jewell and Kabrick, 1981). Consequently, it is the least expensive (Jewell, Dell-Orto, et al., 1981). The plug flow digester can be a horizontal or vertical reactor. The horizontal reactor shown in Figure 28 is the most commonly used configuration. The waste enters on one side of the reactor and exits on the other. Since bacteria are not conserved, a portion of the waste must be converted to new bacteria, which are subsequently wasted with the effluent. Since the plug flow digester is a growth based system, it is less efficient than a retained biomass system. It converts less waste to gas.

Plug flow systems are subject to stratification wherein the sands and silts settle to the bottom and the organic fibers migrate to surface. The stratification can be partially inhibited by maintaining a relatively high solids concentration in the digester.

Periodically, solids must be removed from the plug flow reactor. Since there is no easy way of removing the solids, the reactor must be shut down during the cleaning period. The cost of cleaning can be considerable. Since the solids concentration must be maintained at high levels, dilute milk barn waste is normally excluded from the digester. Plug flow reactors are normally heated by a hot water piping system within the reactor. The hot water piping system can complicate the periodic cleaning of the reactor.

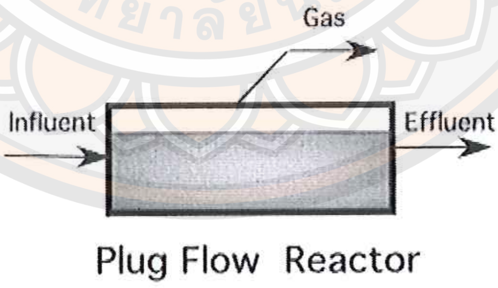

Figure 28 Plug Flow Reactor

Source: Burke D.A., 2001

The plug flow reactor is a simple, economical system. Applications are limited to concentrated dairy manure containing a minor amount of sand and silt. If stratification occurs because of a dilute waste or excess sand, significant operating costs will be incurred.

Contact Digesters (High Rate)

The contact reactor is a high rate process that retains bacterial biomass by separating and concentrating the solids in a separate reactor and returning the solids to the influent (Ettinger, Witherow, et al., 1957; Loehr, 1974). More of the degradable waste can be converted to gas since a substantial portion of the bacterial mass is conserved. The contact digester can be either completely mixed or plug flow. It can be operated in the thermophilic or mesophilic range. The contact reactor can treat both dilute and concentrated waste provided the separator can concentrate the digester effluent solids sufficiently to enhance the process.

A wide variety of separators have been tested over the past 30 years. Initially gravity separators (settling tanks), or solids thickeners were used. It was soon discovered that the solids could not be sufficiently concentrated in a gravity separator without degassing to remove the gas bubbles attached to the solids. Actively fermenting digester effluent containing gas bubbles floated rather than settled in the separator. Lamella or plate separators have also been used to concentrate the biomass after degassing. Both of these gravity-settling techniques are not effective for concentrated digester solids. Gravity separation techniques are effective with dilute waste following a completely mixed reactor. Separation requires several days of detention (Duke Engineering & Services, 2001). The completely mixed digester will prevent stratification. The effluent is then allowed to separate by gravity in the separation reactor. The digester solids concentration should be less than 2.5% for gravity separation to be used. Long separator detention times are required.

Mechanical separation devices have been tested to reduce the detention time required by gravity separation. Centrifuges, gravity belts, membranes, and other mechanical separators have been used with limited success. These disruptive devices have been shown to inhibit the bacterial consortia and thus limit the effectiveness of the contact process.

Burke used gas flotation to separate and concentrate the digester effluent for the efficient and tranquil recovery of the anaerobic consortia. The process has been used for the digestion of manure (Burke 1998), sewage sludge and potato waste (Burke, 1997). It has been shown to be effective for concentrating the biomass from actively fermenting digester liquors without the need for degassing. The process has been referred to as the AGF or "anoxic gas flotation" process. Gas flotation can achieve significantly greater biomass concentrations than gravity separation without the adverse consequences associated with disruptive separation techniques.

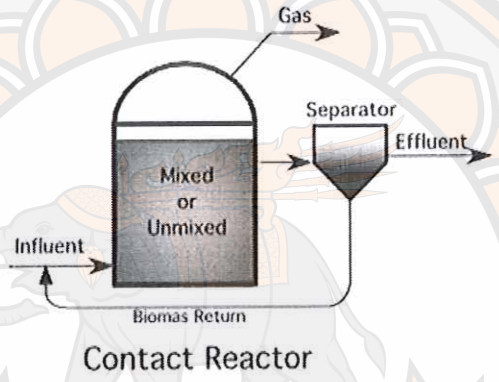

Figure 29 Contact Reactor

Source: Burke D.A., 2001

Gas flotation can also remove enzymes (Burke, et al., 1997), organic acids (Burke, 1997) and other products of digestion that cannot be removed through settling or other mechanical means. Finally, gas flotation can be performed in a non-mechanical manner, which is simple to operate and maintain.

During the contact process, refractory organic and inorganic solids accumulate within the system. The accumulated sands, silts, and non-degradable organic fibers dictate the rate of solids wasting. Wasting the nonbiodegradable solids causes the loss of bacterial mass and reduced process efficiency. The anaerobic contact process can utilize mechanical separating devices to remove refractory solids from the digestion system (Burke, 2000).

Sequencing Batch Reactors (High Rate)

A sequencing batch reactor is a contact digester, which utilizes the same tank for digestion as well as separation. In a sequencing batch reactor the same tank is used to digest the waste and separate the biomass from the effluent liquor (Dugba, et al., 1997). Generally, two or more tanks are used. The tanks are operated in a fill and draw mode. The separation is accomplished by gravity. Consequently, a more dilute, screened waste is treated. Laboratory scale sequencing batch reactors have been used to digest dairy manure.

Contact Stabilization Reactors (High Rate)

The anaerobic contact stabilization process is a more efficient contact process. Burke used the anaerobic contact stabilization process for the digestion of both manure and waste. The process has the advantage of efficiently converting slowly degradable materials such as cellulose in a highly concentrated reactor (Burke, 1997). Organic materials, which can be degraded rapidly, are digested in the contact reactor. The bacteria and slowly degradable organics are removed and degraded in a highly concentrated reactor.

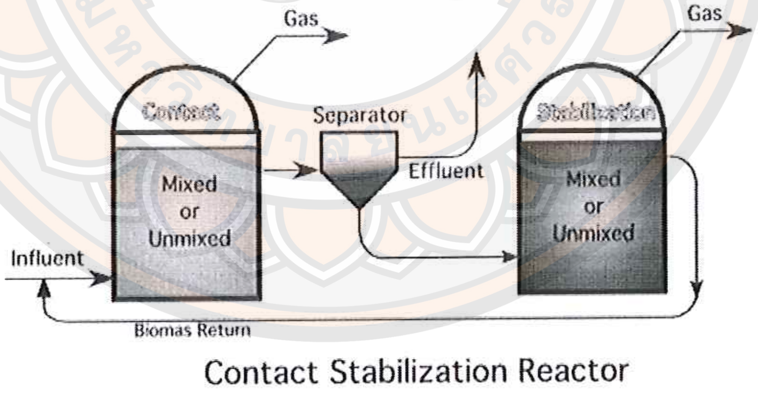

Figure 30 Contact Stabilization Reactor

Source: Burke D.A., 2001

Phased Digesters

Both acid phased and temperature phased digestion have been used to convert municipal sludge to gas. Acid phased digestion (Ghosh, 1987) takes advantage of the fact that the acid forming bacteria have a much higher growth rate than the methanogens.

Consequently, the initial reactor can be much smaller than the subsequent methane producing digester. Acid phased digestion offers greater efficiency in the size of the anaerobic digesters. Acid phased digestion has not been applied to dairy waste.

Temperature phased digestion has been applied to the digestion of sewage sludge. The initial digester is operated in the thermophilic mode followed by a second digester, which is operated in the mesophilic mode. In the first thermophilic digester, pathogens are destroyed. In the second mesophilic digester, the mesophilic bacteria consume the organic acids created in the thermophilic reactor. Consequently, the odors associated with a thermophilic effluent are eliminated while achieving the desired pathogen destruction.

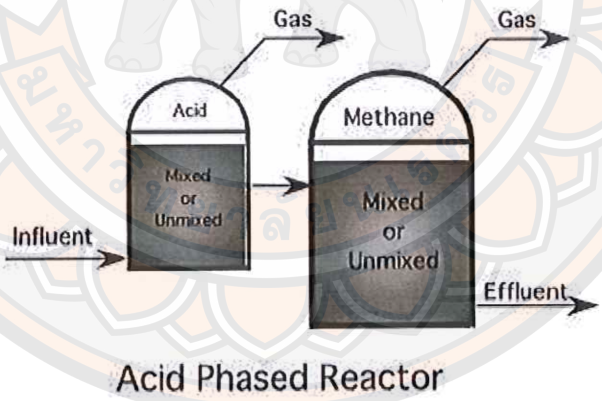

Figure 31Acid Phased Digester

Source: Burke D.A., 2001

Temperature phased digestion has been used to digest dairy manure (Dugba, et al., 1997).In addition it must be pointed out that completely mixed reactors are not completely effective in removing pathogens.

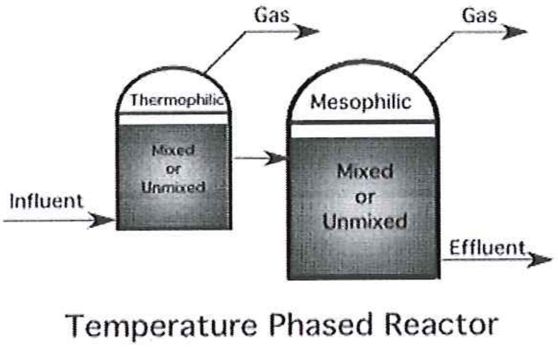

Figure 32 Temperature Phased Digester

Source: Burke D.A., 2001

Hybrid Processes

A number of hybrid processes have been developed and applied to many different kinds of waste materials. The hybrid processes incorporate a combination of the previously described configurations.

5 Solar Energy Collectors

Solar energy collectors are special kinds of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device that absorbs the incoming solar radiation, converts it into heat, and transfers the heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days.

There are basically two types of solar collectors: non-concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. Concentrating collectors are suitable for high-temperature applications. Solar collectors can also be distinguished by the type of heat transfer liquid used (water, non-freezing liquid, air, or heat transfer oil) and whether they are covered or uncovered. A large number of solar collectors are available on the market. A comprehensive list is shown in Table 11.

Solar energy collectors are basically distinguished by their motion station ary, single-axis tracking, and two-axis tracking and the operating temperature. First, we'll examine the stationary solar collectors. These collectors are permanently fixed in position and do not track the sun. Three main types of collectors fall into this category:

1. Flat-plate collectors (FPCs).
2. Stationary compound parabolic collectors (CPCs).
3. Evacuated tube collectors (ETCs).

Table 11 Solar Energy Collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Cylindrical trough collector (CTC)	Tubular	15–50	60–300
	Parabolic trough collector (PTC)	Tubular	10–85	60–400

Table 11 (cont.)

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Two-axis tracking	Parabolic dish reflector (PDR)	Point	600–2000	100–1500
	Heliostat field collector (HFC)	Point	300–1500	150–2000

Note: Concentration ratio is defined as the aperture area divided by the receiver /absorber area of the collector.

Flat-Plate Collectors (FPCs)

A typical flat-plate solar collector is shown in Figure 33. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and transferred to the transport medium in the fluid tubes, to be carried away for storage or use. The underside of the absorber plate and the two sides are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate or they can be an integral part of the plate. The liquid tubes are connected at both ends by large-diameter header tubes. The header and riser collector is the typical design for flat-plate collectors. An alternative is the serpentine design shown on the right-hand side of Figure 33 This collector does not present the potential problem of uneven flow distribution in the various riser tubes of the header and riser design, but serpentine collectors cannot work effectively in thermosiphon mode (natural circulation) and need a pump to circulate the heat transfer fluid. The absorber plate can be a single sheet on which all risers are fixed, or each riser can be fixed on a separate fin, as shown in Figure 33

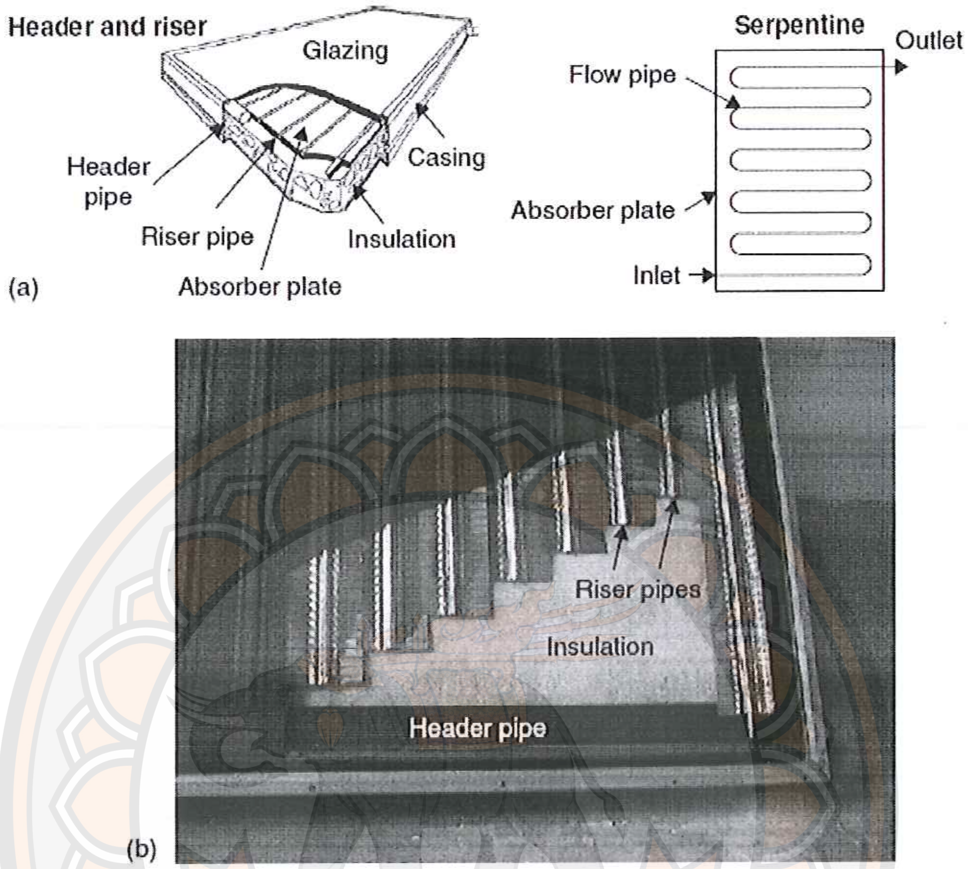

Figure 33 Typical flat-plate collector. (a) Pictorial view of a flat-plate collector. (b) Photograph of a cut header and riser flat-plate collector

Source: Soteris A. Kalogirou, 2014

The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector because the glass is transparent to the shortwave radiation received by the sun, but it is nearly opaque to longwave thermal radiation emitted by the absorber plate (greenhouse effect).

The advantages of flat-plate collectors are that they are inexpensive to manufacture, they collect both beam and diffuse radiation, and they are permanently fixed in position, so no tracking of the sun is required. The collectors should be oriented directly toward the equator, facing south in the Northern Hemisphere and north in the Southern Hemisphere. The optimum tilt angle of the collector is equal to the latitude of the location, with angle variations of 10° to 15° more or less, depending on the application. If the application is solar cooling, then the optimum angle is latitude -10° so that the sun will be perpendicular to the collector during summertime, when the energy will be mostly required. If the application is space heating, then the optimal angle is latitude +10°; whereas for annual hot water production, it is latitude +5°, to have relatively better performance during wintertime, when hot water is mostly required.

The main components of a flat-plate collector, as shown in Figure 33, are the following:

1. **Cover**. One or more sheets of glass or other radiation-transmitting material.

2. **Heat removal fluid passageways**. Tubes, fins, or passages that conduct or direct the heat transfer fluid from the inlet to the outlet.

3. **Absorber plate**. Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. A typical attachment method is the embedded fixing shown in the detail of Figure 34. The plate is usually coated with a high-absorptance, low-emittance layer.

4. **Headers or manifolds**. Pipes and ducts to admit and discharge the fluid.

5. **Insulation**. Used to minimize the heat loss from the back and sides of the collector.

6. **Container**. The casing surrounds the aforementioned components and protects them from dust, moisture, and any other material.

Flat-plate collectors have been built in a wide variety of designs and from many different materials. They have been used to heat fluids such as water, water plus antifreeze additive, or air. Their major purpose is to collect as much solar energy as possible at the lowest possible total cost. The collector should also have a long effective life, despite the adverse effects of the sun's ultraviolet radiation and corrosion and clogging because of acidity, alkalinity, or hardness of the heat transfer fluid, freezing of water, or deposition of dust or moisture on the glazing and breakage of the glazing from thermal expansion, hail, vandalism, or other causes. These causes can be minimized by the use of tempered glass.

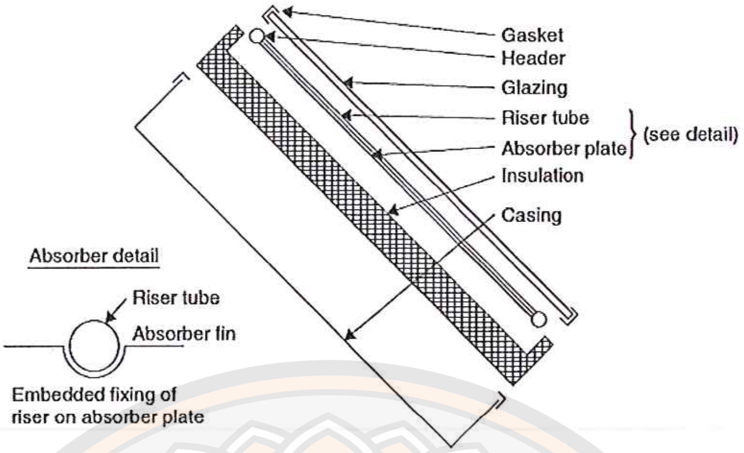

Figure 34 Exploded view of a flat-plate collector and absorber details

Source: Soteris A. Kalogirou, 2014

Compound Parabolic Collectors (CPCs)

Compound parabolic collectors (CPCs) are non-imaging concentrators. They have the capability of reflecting to the absorber all of the incident radiation within wide limits. Their potential as collectors of solar energy was pointed out. The necessity of moving the concentrator to accommodate the changing solar orientation can be reduced by using a trough with two sections of a parabola facing each other.

Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation entering the aperture within the collector acceptance angle finds its way to the absorber surface located at the bottom of the collector. The absorber can take a variety of configurations. It can be flat, bifacial, wedge, or cylindrical.

Compound parabolic collectors should have a gap between the receiver and the reflector to prevent the reflector from acting as a fin conducting heat away from the absorber. Because the gap results in a loss of reflector area and a corresponding loss of performance, it should be kept small. This is more important for flat receivers.

Evacuated Tube Collectors (ETCs)

Conventional simple flat-plate solar collectors were developed for use in sunny, warm climates. Their benefits, however, are greatly reduced when conditions become unfavorable during cold, cloudy, and windy days. Furthermore, weathering influences, such as condensation and moisture, cause early deterioration of internal materials, resulting in reduced performance and system failure. Evacuated heat pipe solar collectors (tubes) operate differently than the other collectors available on the market. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Figure 35.

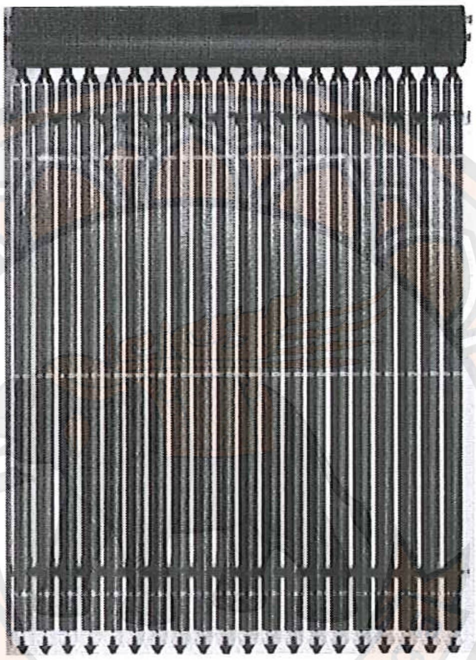

Figure 35 An evacuated tube collector

Source: Soteris A. Kalogirou, 2014

Evacuated tube collectors use liquid-vapor phase change materials to transfer heat at high efficiency. These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate). Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid (e.g., methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid and the vapor travels to the heat sink region, where it condenses and releases its latent heat. The condensed fluid returns to the solar collector and the process is repeated. When these tubes are mounted, the metal tips project into a heat exchanger (manifold). Water or glycol flows through the manifold and picks up the heat from the tubes. The heated liquid circulates through another heat exchanger and gives off its heat to a process or water stored in a solar storage tank. Another possibility is to use the ETC connected directly to a hot water storage tank.

Solar hot water systems

Solar hot water systems can be classified into two categories, passive and active. Passive systems typically use gravity to transfer the collected solar energy to the storage tank or directly to the load. These systems are often referred to as "thermosyphon" systems. Active systems require a mechanical pump to transfer the collected thermal energy to the storage tank. A schematic of these two general systems is shown in Figure 36.

(a)

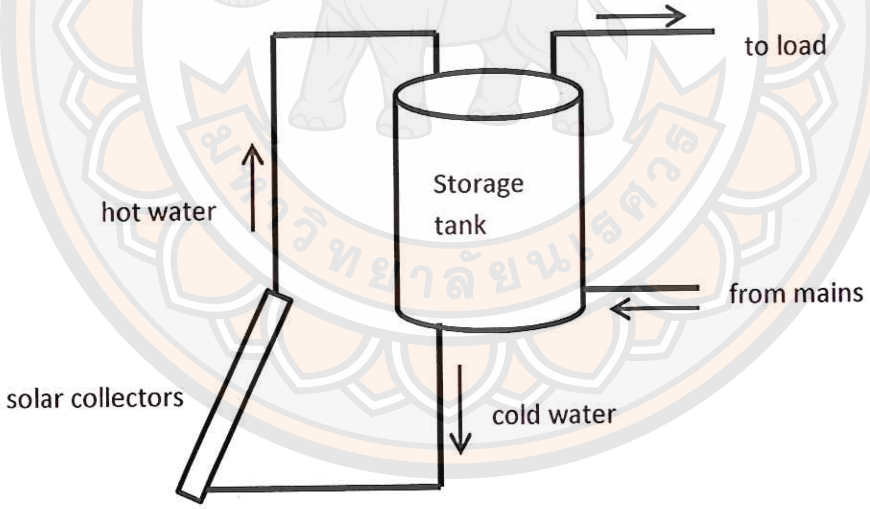

Figure 36 **Schematic diagrams of: (a) typical passive and (b) typical active solar hot water system**

Source: http://www.asse-plumbing.org, 2014

(b)

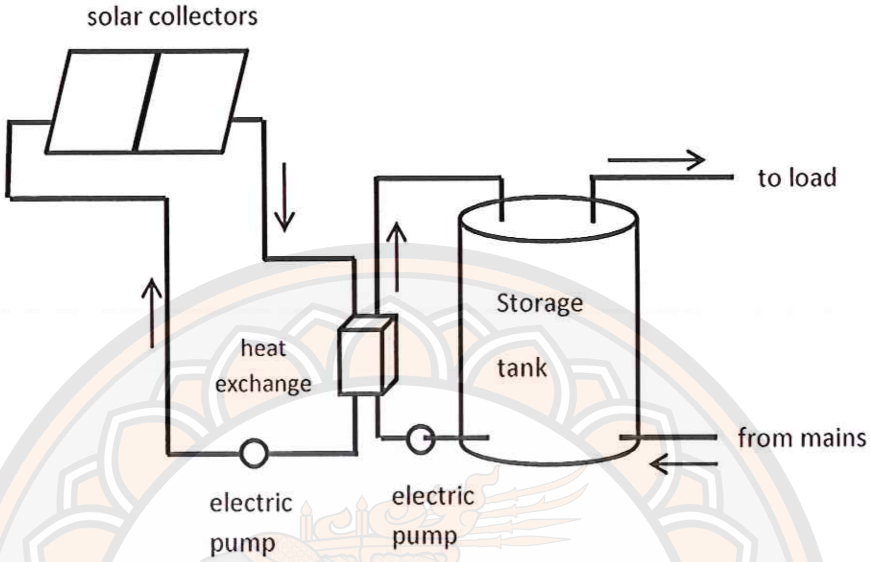

Figure 36 (cont.)

For thermosyphon systems, Figure 36(a), the storage tank is mounted above the collector, and the entire apparatus is located on the roof of the residence. Hot water is delivered to the household by gravity feed. The water circulates through the solar collector and into the tank by natural convection whenever there is sufficient available solar energy to establish a density difference between the cold fluid in the storage tank and the fluid in the solar collector.

Figure 36 (b) shows a schematic of a typical active system. Active systems require a pump to circulate the fluid through the solar collectors, and usually a second pump to circulate water from the storage tank through a heat exchanger.

Solar hot water direct (Open Loop) systems (Active)

1. Differential controller operated system

The direct pumped system, illustrated in Figure 37 below, has one or more solar energy collectors installed on the roof and a storage tank somewhere below, usually in a garage or utility room. A pump circulates the water from the tank up to the collector and back again. This is called a direct (or open loop) system because the sun's heat is transferred directly to the potable water circulating through the collector tubing and storage tank; no anti-freeze solution or heat exchanger is involved.

This system has a differential controller that senses temperature differences between water leaving the solar collector and the coldest water in the storage tank. When the water in the collector is about 15-20° F warmer than the water in the tank, the pump is turned on by the controller. When the temperature difference drops to about 3-5° F, the pump is turned off. In this way, the water always gains heat from the collector when the pump operates. A flush-type freeze protection valve installed near the collector provides freeze protection. Whenever temperatures approach freezing, the valve opens to let warm water flow through the collector. The collector should also allow for manual draining by closing the isolation valves (located above the storage tank) and opening the drain valves. Automatic recirculation is another means of freeze protection. When the water in the collector reaches a temperature near freezing, the controller turns the pump on for a few minutes to warm the collector with water from the tank.

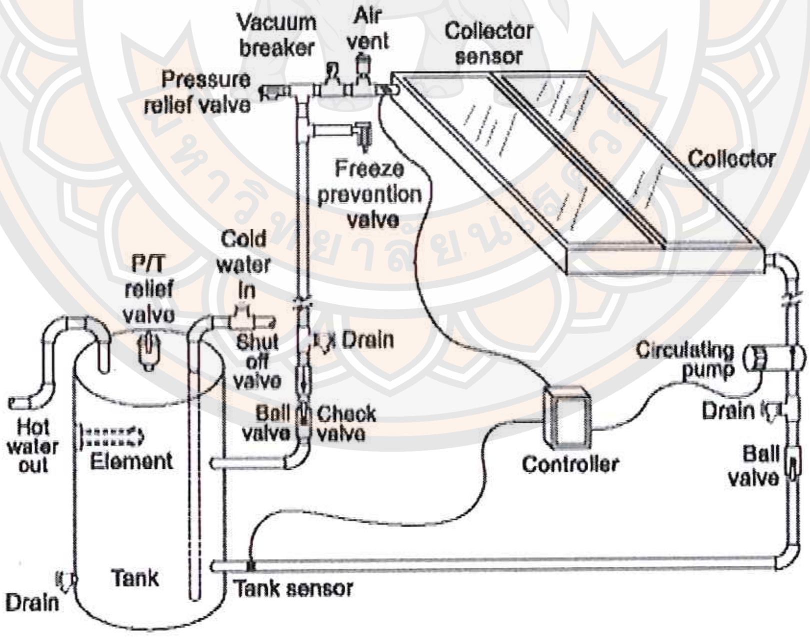

Figure 37 The direct pumped system

Source: www.wadebyrd.com, 2014

2. Photovoltaic operated system

The system shown in Figure 38 below, differs from other direct pumped systems in that the energy to power the pump is provided by a photovoltaic (PV) panel. The PV panel converts sunlight into electricity, which in turn drives the direct current (dc) pump. In this way, water flows through the collector only when the sun is shining. The dc pump and PV panel must be suitably matched to ensure proper performance. The pump starts when there is sufficient solar radiation available to heat the solar collector. It shuts off later in the day when the available solar energy diminishes. As in the previous systems, a thermally operated valve provides freeze protection. Common appliance timers also may control solar system operation. These timers must incorporate battery backup in the event of power failures.

The timer is set to operate during a period of the day when solar radiation is available to heat the potable water. In order to avoid loss of energy from the tank during overcast days, the collector feed and return lines are both connected at the bottom of the storage tank with a special valve. During normal operation, natural stratification allows the warmer water to rise to the top of the tank.

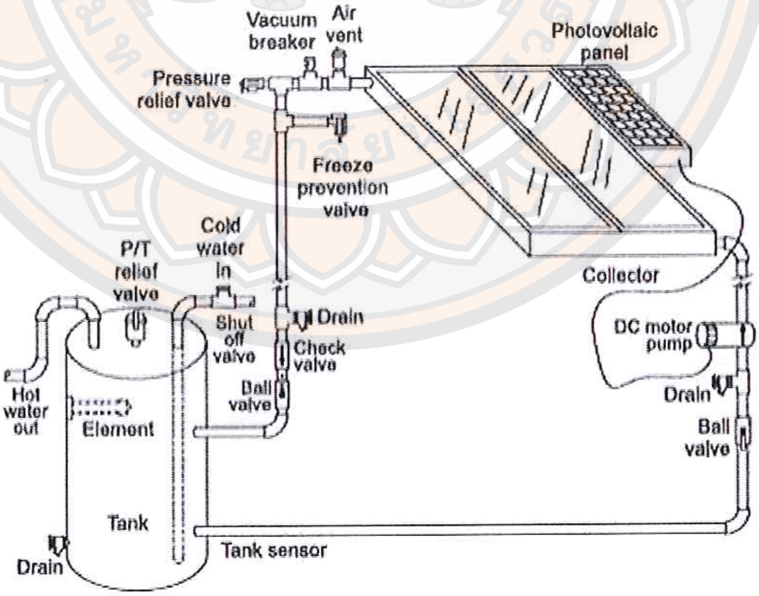

Figure 38 Photovoltaic operated system

Source: www.wadebyrd.com, 2014

Solar hot water direct (Open Loop) systems (Passive)

1. Integral Collector Storage (ICS) System

In the integral collector storage solar system shown in Figure 39 at right, the hot water storage system is the collector. Cold water flows progressively through the collector where it is heated by the sun. Hot water is drawn from the top, which is the hottest, and replacement water flows into the bottom. This system is simple because pumps and controllers are not required. On demand, cold water from the house flows into the collector and hot water from the collector flows to standard hot water auxiliary tank within the house. A flush type freeze protection valve is installed in the top plumbing near the collector. As temperatures near freezing, this valve opens to allow relatively warm water to flow through the collector to prevent freezing. In south Florida and certain areas of central Florida, the thermal mass of the large water volume within the ICS collector provides a means of freeze protection.

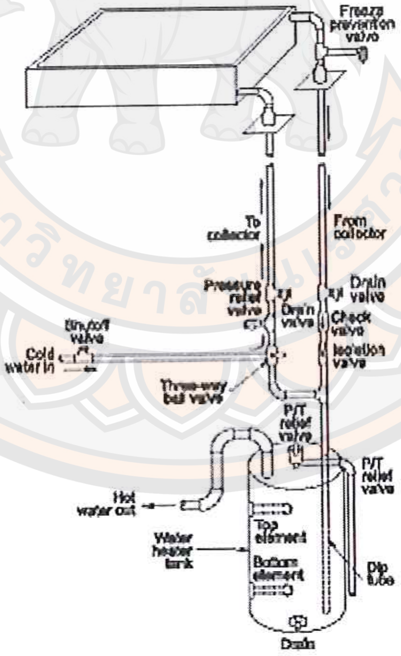

Figure 39 Integral Collector Storage (ICS) System

Source: www.wadebyrd.com, 2014

2. Thermosiphon System

A typical thermosiphon system is indicated in Figure 40 below. As the sun shines on the collector, the water inside the collector flow-tubes is heated. As it heats, this water expands slightly and becomes lighter than the cold water in the solar storage tank mounted above the collector. Gravity then pulls heavier, cold water down from the tank and into the collector inlet. The cold water pushes the heated water through the collector outlet and into the top of the tank, thus heating the water in the tank.

A thermosiphon system requires neither pump nor controller. Cold water from the city water line flows directly to the tank on the roof. Solar heated water flows from the rooftop tank to the auxiliary tank installed at ground level whenever water is used within the residence. This system features a thermally operated valve that protects the collector from freezing. It also includes isolation valves, which allow the solar system to be manually drained in case of freezing conditions, or to be bypassed completely.

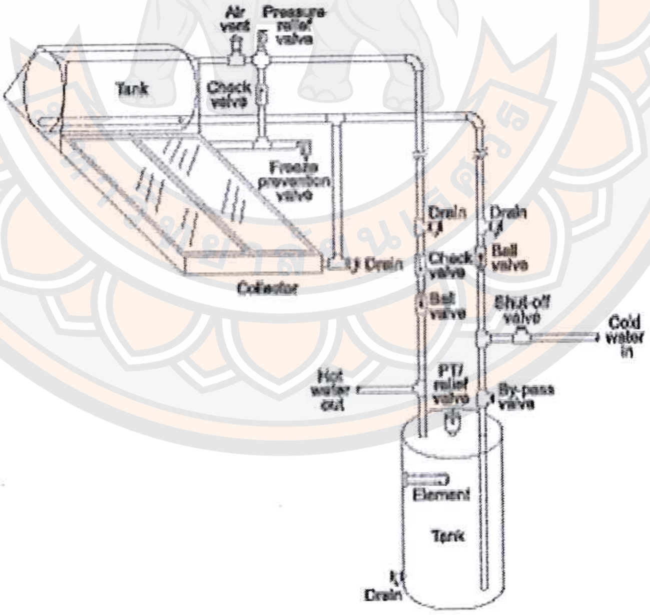

Figure 40 A typical thermosiphon system

Source: www.wadebyrd.com, 2014

Solar hot water indirect (Closed Loop) systems

1. Indirect Pumped System

This system design is common in northern climates, where freezing weather occurs more frequently. An antifreeze solution circulates through the collector, and a heat exchanger transfers the heat from the antifreeze solution to the tank water. When toxic heat exchange fluids are used, a double-walled exchanger is required. Generally, if the heat exchanger is installed in the storage tank, it should be in the lower half of the tank.

The system illustrated in Figure 41 at right is an example of this system type. Here a heat transfer solution is pumped through thecollector in a closed loop. The loop includes the collector,connecting piping, the pump, an expansion tank and a heat exchanger. A heat exchanger coil in the lower half of the storage tank transfers heat from the heat transfer solution to the potable water in the solar storage tank. An alternative of this design is to wrap the heat exchanger around the tank. This keeps it from contact with potable water.

The brain of the system is a differential controller. In conjunction with collector and tank temperature sensors, the controller determines when the pump should be activated to direct the heat transfer fluid through the collector. The fluid used in this system is a mixture of distilled water and antifreeze similar to that used in automobiles. This type of fluid freezes only at extremely low temperatures so the system is protected from damage caused by severe cold.

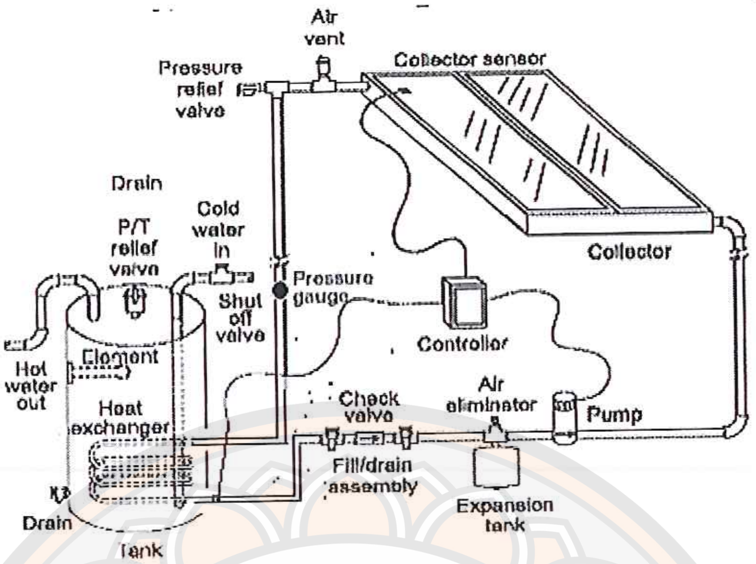

Figure 41 Solar hot water indirect Pumped System

Source: www.wadebyrd.com, 2014

2. Drain Back System

A fail-safe method of ensuring that collectors and collector loop piping never freeze is to remove all water from the collectors and piping when the system is not collecting heat. This is a major feature of the drain back system illustrated in Figure 42 at left. Freeze protection is provided when the system is in the drain mode. Water in the collectors and exposed piping drains into the insulated drain-back reservoir tank each time the pump shuts off. A slight tilt of the collectors is required in order to allow complete drainage. A sight glass attached to the drain-back reservoir tank shows when the reservoir tank is full and the collector has been drained.

In this particular system, distilled water is recommended to be used as the collector loop fluid- transfer solution. Using distilled water increases the heat transfer characteristics and prevents possible mineral buildup of the transfer solution. When the sun shines again, the pump is activated by a differential controller. Water is pumped from the reservoir to the collectors, allowing heat to be collected. The water stored in the reservoir tank circulates in a closed loop through the collectors and a heat exchanger at the bottom of the solar tank. The heat exchanger transfers heat from the collector loop fluid to the potable water in the solar tank.

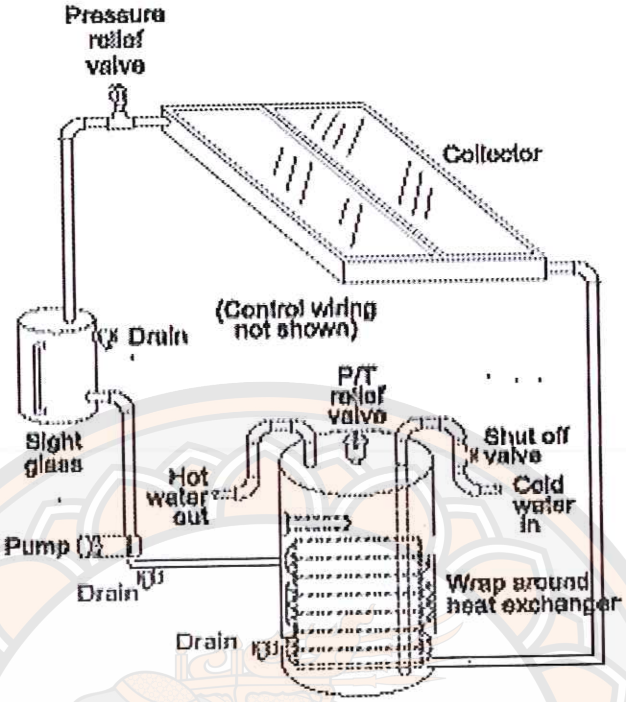

Figure 42 The drain back system

Source: www.wadebyrd.com, 2014

Table 12 A rough comparison of solar hot water systems

Characteristic	ICS (Batch)	Thermosiphon	Active direct	Active indirect	Drainback	Bubble Pump
Low profile-unobtrusive			✓	✓	✓	✓
Lightweight collector			✓	✓	✓	✓
Survives freezing weather			✓	✓	✓	✓
Low maintenance	✓	✓	✓		✓	✓
Simple: no ancillary control	✓	✓				✓

Table 12 (cont.)

Characteristic	ICS (Batch)	Thermosiphon	Active direct	Active indirect	Drainback	Bubble Pump
Retrofit potential to existing store			✓	✓	✓	✓
Space saving: no extra storage tank	✓	✓				

Operation of the solar hot water

Solar hot water performs three basic operations:

1. Collection: solar radiation is collected and converted to heat energy by a solar collector.
2. Transfer: circulating fluids transfer the heat to a storage tank using a heat exchanger.
3. Storage: hot water is stored until needed for use.

Collection

The first operation is based on the "greenhouse effect". The solar collector is mounted on or near the building, facing south. Sunlight passing through glass or plastic glazing strikes an absorber plate coated with a radiation-absorbing material. The absorber plate converts the sunlight into heat, which is prevented from escaping by the glazing.

The most common solar collectors used in solar water heaters are "liquid flat plate" and "evacuated tube" collectors. A flat plate collector consists of a shallow rectangular box with a transparent glass or plastic "window" covering a flat black painted plate. The black plate acts as the absorber of solar energy and the solar collector coolant passes through pipes attached to the plate.

Transfer

The second operation involves the transfer of heat from the collector to the water storage. In some solar hot water, the solar collector coolant is pumped from the collector to the storage unit. In others, the sun heats the storage tank directly, or the fluid in the collector is heated and rises naturally to a storage tank above the collector. This latter type of solar hot water is referred to as a thermosiphon system.

Two kinds of heat exchangers can be used to transfer the heat from the solar collector coolant to the cold water in the case of a closed loop system. The first kind is an internal or immersion heat exchanger, where the heat transfer between the hot solar collector coolant and the cold water occurs inside the storage tank. The second kind is an external heat exchanger, where the heat transfer between the solar collector coolant and the water occurs outside the storage tank.

Storage

The third operation involves the storage of the solar hot water in an insulated tank. Hot water is drawn from the tank when tap water is used and cold make-up water enters at the bottom of the tank.

Solar hot water have a larger hot water storage capacity than electric, gas, or other water heaters. This is because solar heat is available only during the day and sufficient hot water must be collected to meet evening and early morning needs, and possibly the needs for the following days in the event of inclement weather and low solar energy availability.

The Basics of Design (David A. Bainbridge, 2012).

Radiation

Any object at a temperature greater than absolute zero (-273°C) emits radiation with the wavelength and intensity dependent on temperature. Radiation flows from a warmer object to a cooler object. This would ultimately result in thermal equilibrium if no other energy were added to or taken away from the objects. Radiation is emitted by the sun, from the earth, and from your solar water heater. Shortwave radiation from the sun is collected by your Integral Passive Solar Water Heater (IPSWH) for heating. Longwave (thermal) radiation to space-emitted from your IPSWH to the cold night sky, for example-is responsible for much unwanted cooling. Both types of radiation are therefore important in IPSWH design. The graph below shows the ideal curves of raditation emitted from the sun and earth.

The sun's path across the sky determines the amount of solar radiation reaching the earth's atmosphere-and therefore varies with the seasons and with different locations on earth. The sun's position is described by its elevation above the horizon, altitude, and by its bearing from the true north, azimuth. The change in elevation and azimuth over the season is critically important in IPSWH design. At 40° north latitude the sun is at an altitude of 30° at noon on December 21 and almost 70° during the summer. In summer it traverses an arc of 240° from east to west while in winter it covers only 120°.

Not all of the radiation striking the edge of the earth's atmosphere reaches the surface of the earth. The reduction in energy is primarily due to reflection and absorptions by carbon dioxide and water vapor in the atmosphere. The actual amount of direct radiation received varies with the atmospheric content, cloudiness, and the solar angles (which determine path length). On the average, 31 percent of the solar radiation to the atmosphere reaches the earth's surface as direct radiation. The radiation that reaches the earth after reflection or refraction in the atmosphere is known as diffuse radiation. Again, the amount received will vary with the atmospheric content, cloudiness, and solar angles. On the average about 22 percent of the solar radiation to the atmosphere reaches the earth as diffuse radiation.

The total of the diffuse and direct components of solar radiation reaching the ground is known as the global radiation. (The remaining 47 percent of solar radiation is absorbed by particles in the atmosphere or reflected off them back into space.) On a cloudy day little direct radiation may be received and diffuse radiation may account for almost all of the energy reaching the earth's surface. Diffuse radiation is often assumed for simplicity to be uniformly distributed over the sky, but the intensity is in fact usually much stronger near the sun.

Radiation at wavelengths longer than 3 microns is referred to as thermal radiation. This is an important element of IPSWH design as it covers much of the energy exchange within a collector and unwanted radiant cooling of the collector. In addition to the shortwave radiation received directly or indirectly from the sun, the earth also receives thermal radiation from the water and gas molecules and dust particles in the atmosphere. The difference between the total radiation received, and that radiated back from the earth into space is referred to as the net outgoing radiation when more is radiated from the earth than to the earth. This net outgoing radiation is thermal radiation, primarily at wavelengths between 6 and 15 microns.

Maximum net outgoing radiation will occur to a cold, clear night sky. In Blue Hill, Massachusetts F.A. Brooks compiled a table of variation in net outgoing radiation to the cold night sky as a function of the zenith angle. He found that the greatest radiation loss occurs directly overhead (the zenith) and that the rate was high down to about 20 degrees above the horizon.

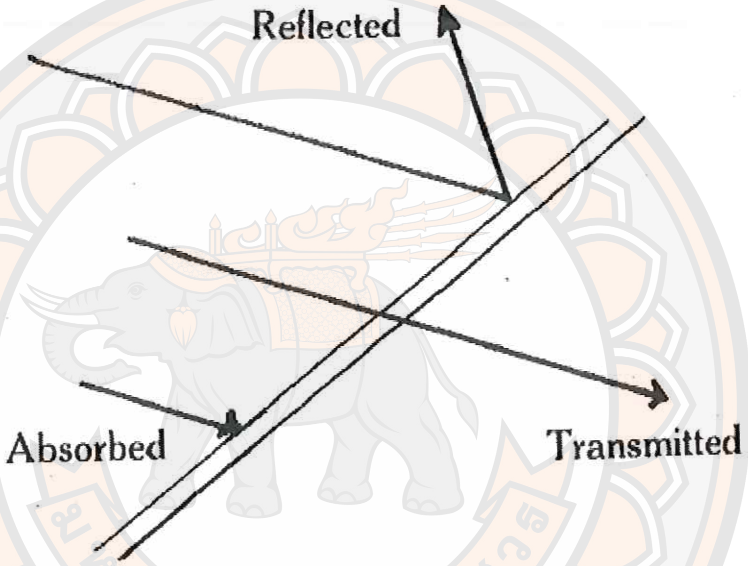

Figure 43 Thermal radiation

Source: David A. Bainbridge, 2012

Clouds can greatly reduce net outgoing radiation to the night sky because they emit thermal radiation to the earth from the atmosphere and thus increase the total radiation received. The exact effect depends on the height of the clouds, their density, and temperature. This blocking of outgoing radiation by clouds can help reduce the night radiation loss from an uncontrolled IPSWH, i.e., one without some form of glazing control.

Trees, walls and other structures can also significantly decrease night sky cooling. The reduction in radiative loss depends on the configuration of the obstruction and on its placement. Unfortunately, most objects which will reduce radiative loss will also block incoming sunlight unless they are movable and operate only at night.

Materials vary in their ability to emit radiation. The emittance of materials is important in IPSWH design because outgoing radiation loss from the IPSWH can be reduced by choosing materials which emit little radiation. Materials that collect energy effectively yet emit little energy are known as selective surfaces. The table below presents the emittance (relative to a 100% "perfect" emittor) for various materials that may be used in an IPSWH.

Table 13 The emittance for various materials in an IPSWH

Materal	Emittance (%)
White paint	95
White enamel on galvanized iron	90
Black paint on aluminum	88
Black lacquer	82
Galvanized iron (oxidized)	28
Galvanized iron (new)	13
Nickel black on galvanized iron	12
Cupric oxide on sheet aluminum	11
Selective surface foil	10
Aluminum foil	8

When radiation strikes a surface, it can be either absorbed, transmitted, or reflected. If it stays in the material it is absorbed; if it passes through the material it is transmitted, and if it bounces off the material it is reflected. The properties of various materials may be quite different and materials must be chosen to ensure that desired performance is achieved. For example, the collector should maximize absorption; the glazing should maximize transmission of incoming radiation yet minimize transmission of outgoing radiation; and the whole assembly should minimize unwanted reflection.

Radiation striking an object is absorbed if the energy is retained by the material. For example, a black hose left in the sun heats up as it absorbs energy from the sun. The percentage of incoming radiation that is absorbed by a material is referred to as its absorptance and is a measure of the ease with which a material or surface collects energy. The table below presents absorptance for various materials in sunlight:

Table 14 Absorptance for various materials in sunlight

Material	Absorptance (%)
Flat black paint	96
Selective Surface foil	95
Black tar paper	93
Very dirty galvanized iron	91
Galvanized steel	65
Shiny aluminum	26

The high absorptance and low cost of black paint makes it a good choice for IPSWH's. The selective surface foils are also good candidates for IPSWH use, particularly if no lids will be used. Ideally we would like a material with high absorptance and very low emittance. Some of the new selective surface foils look quite attractive in this regard, particularly for IPSWH's without movable insulation. Stickney and Nagy found use of a selective surface foil could reduce night heat loss 30 percent and increase daytime gain 25 percent.

Radiation passing through glazing material is said to be transmitted. Transmittance varies not only for different materials but also varies with the wavelength of the radiation. It is therefore desirable to know the spectral transmittance of glazing for passive solar water heating systems. Ideally, the glazing should be very transparent to incoming shortwave radiation but opaque to outgoing long wave (thermal) radiation, because radiant losses may account for over 70 percent of collector heat loss. Typical spectral transmission curves are shown below for common glazing materials. New materials such as "Heat Mirror™" are designed to allow shortwave radiation in, yet prevent thermal radiation from escaping. Some of these materials allow 90 percent of the radiation in (as good as glass) yet reflect 90 percent of the thermal radiation that is trying to escape. These materials are very attractive for IPSWH glazing.

The index of refraction of the material will affect the manner in which the radiation is transmitted. The index of refraction determines how much incoming radiation entering the material at an acute angle will be transmitted directly through and how much of it will be refracted (i.e., deflected from a straight path). A prism provides a good example of refraction-it separates sunlight into the different wavelengths and gives the familiar rainbow. Glass has a lower index of refraction than plastic and hence is typically better at transmitting radiation entering at acute angles. However, the ease of molding and shaping plastic into complex shapes can offset this deficiency.

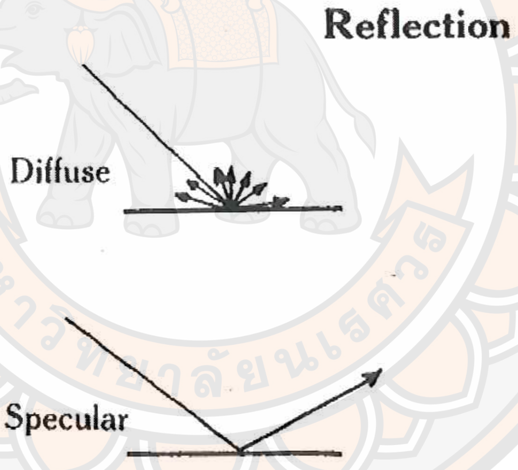

Figure 44 The index of refraction of the material

Source: David A. Bainbridge, 2012

Reflection occurs when radiation bounces off a surface. Reflection can be specular or diffuse. A mirror exhibits specular reflection while white paint exhibits diffuse reflection. The term reflectance describes the ability of a given surface to reflect radiation. The reflectance of a surface is generally given as the percentage of incoming (incident) radiation which is reflected. Reflectance for a given surface also varies with the wavelength of the incident radiation. The reflectance of a material can also be described for both specular and diffuse radiation.

To ensure maximum collection of solar radiation, the design of an IPSWH should minimize unwanted reflection. However, a carefully designed reflector-or a natural reflector such as a snowfield-can be used to increase the solar radiation received.

The following table gives the diffuse reflectance of various surfaces in visible wavelengths. These figures can help you determine how much solar energy will be received at the IPSWH. Reflectance can be especially important for an IPSWH built into a south wall or greenhouse in colder climates (receiving less direct radiation due to the short days and low angle of the winter sun) as the solar radiation received can be increased by using either natural or artificial reflectors.

Table 15 The diffuse reflectance of various surfaces in visible wavelengths

Surface	Diffuse Reflectance (as percent of incident radiation)
Fresh snow	75 – 95
White paint	57 – 90
Old snow	40 – 70
Concrete	40
Dark soil	7 - 10

Shiny surfaces such as aluminum foil demonstrate specular reflectance. The following table gives the reflectance for surfaces with high specular components, again for visible wavelengths. These can be used as exterior reflectors to increase the solar gain of an IPSWH. Use of interior reflectorized surfaces within the IPSWH collector may also be warranted with some designs. The key is whether more energy will be reflected out than gained by redirection. A well insulated box may do just as well if it is all black inside, as resulting thermal exchange will be primarily to the tanks.

Table 16 The reflectance for surfaces with high specular components

Surface	Specular Reflectance (as percent of incident radiation)
Aluminum foil (new)	80 – 85
Mirror, silver backed	88
Mirror, mercury backed	80
Optical reflector, fresh	93

Adding the global and the reflected radiation gives us the total solar radiation received on the surface. This is particularly important for IPSWH's in the higher latitudes where a snowy surface south of a vertical, or near vertical, IPSWH may add 50 percent to the total solar radiation in the coldest month.

Conduction

Next in importance after radiation is conduction or the transfer of energy from molecule to molecule. Insulation reduces conductive heat transfer and is therefore an important consideration in the design and placement of the IPSWH. Insulation is described by its resistance to heat flow, or R value. Typical R values are shown below; the higher the R value the better the insulating value.

Table 17 Insulations to heat flow

Material	R Value (BTU/hour/sq ft/ °F) R value = 5.7 x RSI
Wood	1
Sawdust	2
Fiberglass batts	3
Polystyrene	4
Exp. Polyurethane	6

The insulating value of a material is also influenced by air films and the air flow across the material. A stable air film will increase resistance as much as 0.7 R on a vertical surface. If the air film is moving this increase may drop to 0.2 R.

Glazing can be a major source of heat loss for an IPSWH because even with double pane glass the R value may be only 1.8 including the air films. Some form of glazing control or insulated cover is desirable for an IPSWH in all but the warmest climates. These can be either automatic or manual and can operate either inside or outside the IPSWH.

Convection

Although less important than radiation and conduction, convection-the transfer of energy through air flow-can still be a factor in IPSWH design. This may be flow caused by local differences in density of air (cooler air is heavier) or weather patterns with characteristic winds. The convective flow of air in and out of an IPSWH is known as infiltration. It is affected by design of glazing, walls, framing joints, and movable insulation. Careful detailing, caulking, and sealing can minimize convective heat loss even in areas with consistently high winds.

After the principles concerning energy collection, the next consideration in IPSWH design is energy storage the ability to store the absorbed energy in the form of heat. Fortunately, water is an excellent material for storing heat. It can store one BTU per pound per degree F of temperature rise (4.18 J per g per ºK). Thus the tanks of water provide thermal storage for the collected solar energy. There may also be some cases where a phase change material (pcm) could be incorporated in the IPSWH. These pcm's can store two to four times as much energy as water and might be used to keep operating temperatures at 120°F to 140°F (49°C to 60 C) during the day with extended high temperatures at night as the pcm gives up its stored energy. This would also increase collector efficiency by reducing daytime energy losses.

The understanding of these basic principles of radiation and radiative heat transfer, conduction and convection will help you design a better IPSWH. They should also help you make your home more energy efficient in general.

IPSWH Design

The Six Commandments of IPSWH Design

1. Place IPSWH in a sunny spot.
2. Make it an effective collector.
3. Ensure that it will retain heat.
4. Make it the right size.
5. Make efficient connection to the conserving backup system.
6. Build it to last.

Place IPSWH in a Sunny Spot

Obviously a solar heater won't work very well unless it receives enough sun. Fortunately the sun's path is very predictable, and with only a modest investment of energy and time you can determine how sunny the possible locations for your IPSWH are. In addition to solar access you will have to consider the requirements for connection to your existing systems, so read the suggestions in Rule 5 before committing yourself to a particular IPSWH location.

There are two basic methods to determine how sunny a given location is-observation and calculation. Observation is the simpler method, but it requires much more time. Unless you are very patient, very familiar with your homestead, or a confirmed shutterbug with photos of the south side of your house during all seasons of the year, you may wish to use calculation. However, if you are planning to build your IPSWH only after you have completed other home improvements, you might find that observation is the easier and more accurate method.

The essence of the observation method is using photographs or sketches to chart shadow movement through the seasons. Pay particular attention on December 21, the winter solstice, when the shadows will be longest, and in the fall, when leaves are still on deciduous trees but the sun is lower in the sky. You should make note of shadows throughout the day as well. Probably the best approach would be to keep a record of sun and shadow patterns one weekend day every month for a year.

If you are unwilling to wait and wish to do your solar prospecting straight away, you can calculate your siting using a site evaluator, which indicates the sun's path throughout the year. You can either buy one or make your own. The two commercial models I am familiar with are both fairly easy to use, practical, and accurate. If you are a solar builder, or plan to become one, you might wish to purchase one.

You can also use reflectors to increase solar gain. These can be either natural (bright south snow) or manmade (white, polished aluminum or mirrored panels, fixed or movable). You can probably double your gain with careful use of reflectors.

Keep in mind the weight of the completed heater when you choose a location for it. If you build a 90 gallon (341 l) heater it may weigh more than 600 lbs (272 kg) when full of water. A lightly built roof will require additional bracing to an interior bearing wall.

If no good location in the sun is available on your roof or backyard you may want to build a little platform in the sun for your IPSWH. Quite often this can be integrated with an air lock entrance or shelter for an entrance. Four 4 x 4 inch *(10* x 10 cm) posts provide more than enough support for even a fairly large IPSWH.

Make it an Efficient Collector

This might also be stated another way-"Paint it Black." As you will recall the absorptance of flat black paint is 96 percent, which is about all we can hope for. However, the emittance of black paint is unfortunately fairly high-which lowers the net gain. For those of you with a love of high technology or desire for better performance there is another option that can be considered-selective surfaces. The absorptance of the selective surface may be very close to that of black paint-but it will have much lower emittance.

Ensure That it Will Retain Heat

The most elemental IPSWH, a simple black can in the sun, will work well on a sunny warm day, and this simple design has been used effectively for many years. However, for convenience you may wish to have hot water on cooler days and at night. To do this you will have to ensure that your IPSWH will retain heat better.

The first step is to place your IPSWH in a tight, well insulated box with glazing on the south side to admit the sun's energy. Given this protection your IPSWH can provide hot water even on a very cool day. The level of insulation should be higher than for a house because the temperature difference between inside the heater and outside is much higher. An insulation value of R 25 is suggested for the box in colder climates-equivalent to a six inch wall with fiberglass and one inch of foam board.

The loss back through the glazing can also become important when it is cool outside, and multiple glazing may be desirable. The accompanying map shows suggested layers of glazing for an IPSWH. In milder climates multiple glazings all around the tank may suffice, with no need for an insulated box; this would allow collection from more sun angles.

A new glazing product will be available by the time you read this. "Heat Mirror™" is a specially developed plastic which is transparent to incoming short wave radiation but virtually opaque to thermal radiation. It can be used in the double glazing of an IPSWH. It will be extremely valuable in IPSWH design as it will make lids less important in marginally cool areas, and in cold areas it will make an IPSWH with lids perform better.

Glass is preferred for glazing in an IPSWH because it is very durable. Tempered glass is stronger and safer than regular glass, but more expensive. You may also wish to consider "solar" fiberglass, polycarbonate, or acrylic, because they are lighter, easier to cut and handle, and more resistant to damage. Their life times are generally shorter, however, and they are petroleum based products which can be expected to become more expensive in the future. Make sure the product you select can handle temperatures of 180° to 220°F (82°C to 93°C).

Seconds or used tempered glass can usually be found at reasonable prices, on the order of $6 to $15 for a single 46 x 76 inch (117 x 193 cm) pane and maybe $40 to $60 for the same in double pane. Patio doors are being upgraded by many people and the take outs are often cluttering up the retrofit shops.

The well insulated box must be well sealed or all the hot air will leak out through the cracks. Caulk and seal all connections and joints with a high quality caulk. In areas that will get hot use a silicone caulk that won't break down under higher temperatures.

Your IPSWH with good insulation, tight seal, and multiple glazing will heat up well during the day but can still lose heat at night. This cooling off results primarily from radiation to space and conduction through the glazing. In mild climates or in summer these losses will be acceptable, but in cooler periods or where warmer water is desired in the morning the losses must be reduced.

Heat losses can best be reduced with some form of movable insulation-either inside the glazing, between the glazing, or outside. The easiest place to include this movable insulation is usually the inside-because there is no need to account for wind, rain, hail, ice or snow. This interior movable insulation can be either a drape of some kind, a series of slats or shutters, or a roll shade.

Some of the possible mechanisms for controlling shutters and shades include: heat motors; Freon transfer systems; automatic camper vent operators; electric trailer tongue jacks; air shock absorbers; bicycle pumps and bicycle tubes; hydraulic lifters; casement window operators; vent actuators; bicycle, car, and aircraft control cables; bicycle gears and hubs; rubber bands (rubber contracts as it warms up); photovoltaic motors; etc. Some of the possibilities are suggested in the accompanying diagrams.

The two ends of the spectrum are a simple manual control, requiring little money or sophistication, but considerable force; and an automatic photovoltaic drive requiring very little energy but considerable expense and sophistication. The tradeoffs are always there, so consider the options before deciding. If you want to automate shutters and drapes throughout the house you might consider a home controller using signals in the **110v** lines to trigger operations.

Exterior movable insulation (insulated covers or shutters) can also be practical. They offer the advantage of increasing collector area if the inside of the lids are reflectorized. These covers will prove most practical where snow loads and high winds are less common. They can fold down, up, or to the side in a variety of ways. These exterior shutters can also be manual or automatic. Where access is difficult an automatic system might be preferred. For a readily accessible system a simple manual lid will prove workable.

The rigid forms are attractive insulation for these movable covers because of their strength and high thermal resistance. Build a strong wood or metal frame with aluminum or wood skins and provide plenty of hinge for strength. Use weatherstrip to get a tight seal when it's closed.

Insulation between the glazing may also become more common as commercial systems are developed. You might also build your own although this will be more challenging. Venetian type blinds and interlocking slats have been available for many years in Europe and Israel and might provide some good ideas on how to do this type of insulation.

A second approach to reduce heat loss is to locate the IPSWH in a greenhouse or in the house itself. This not only reduces the heat loss during the day and at night, but at night would also benefit from the movable insulation system (e.g., insulated shutters) provided for the greenhouse or house glazing. Steve Baer has also designed IPSWH's with the tank in a skylight assembly for preheating only.

Another interesting way to reduce heat losses has been developed by Conrad Heeschen and others. They turn the collector over so it faces down and use a reflector to guide solar radiation to it. This approach may be worth pursuing further, particularly if the building roof or other building element can be used as a reflector.

The use of a selective surface will also reduce heat lossespossibly with less cost and inconvenience than movable insulation. With a selective surface absorptance may be a little less but emissivity is much lower, 10 percent versus 88 percent for black paint, and the net gain over a day will be higher even if no glazing or movable insulation is used.

The design of the heater can also help keep the water as warm as possible for the user. Vertical tanks allow greater stratification to occur-keeping temperatures as warm as possible. Reducing internal mixing with baffles and carefully designed cold water entry can also help. A controlled antimixing entry can be made by directing entry water in a manner that will affect only the colder water at the bottom or end of the tank.

Make it the Right Size

The general rule of thumb for IPSWH design is to allow about 30 gallons (114 I) of storage per person per day. Thus, a family of three would require 90 gallons (341 I) in the IPSWH. This should be more than enough for a conserving household and would give carryover for a day or two of cloudy weather.

To provide adequate collection for this storage, figure that in a temperate climate no more than 2.5 gallons of water per sq ft of collector (100 I per sq m) should be included. The 90 gallon (341 l) water heater would then require at least 36 sq ft (3.3 sq m) of collector.

A more precise determination of the amount of storage required will depend on the expected water use, climate, type of IPSWH, and type of backup system (if any). Demand depends in large measure on the family profile of the users, the type of facilities in use, and the care with which they are used. A family with children (especially if still in diapers) would be expected to use more hot water than a family without children.

The time of demand also affects IPSWH storage and design requirements. The best performance can be achieved by using hot water primarily after midday. This allows the highest temperatures to develop. If hot water is wanted in the early morning then use should either be scheduled to allow recovery in the late afternoon or sufficient capacity should be left after evening use.

The use of water conserving fixtures can considerably reduce the waste of hot water. The key items are flow restrictors for showers and faucets, which are fortunately inexpensive. Water conserving appliances are often slightly more expensive but will save much more than they cost over their lifetimes. The following table suggests the savings possible using conservation devices.

Even if you do not have any solar access for an IPSWH you can still implement your own water conservation strategy-to do more with less.

The careful use of hot water can add further savings. These additional steps include hand washing dishes and batching wash loads carefully so cold water can be used when it will suffice.

And if very careful use is combined with the best conservation minded fixtures and appliances, even more dramatic savings can be achieved. This level of saving will require "ecotopian" consciousness and custom built fixtures-but is worth careful consideration from anyone concerned about the future of our tattered spaceship Earth.

Make a Safe and Efficient Connection to a Conserving Backup System

One of the most important considerations in developing any successful solar system is diligently applying conservation measures to reduce load. IPSWH's are no exception-conservation measures include addition of flow restrictors, aerators, and water conserving appliances. A heat exchanger can also be applied to save the heat energy that is now lost when warm gray water leaves the house. In addition, the connection between IPSWH and the water system should be made as efficient as possible in order to reduce line losses. This involves reducing distances wherever possible and carefully insulating these lines.

The insulation should have a high resistance to heat flow and be very durable. The best system is one with one to two inches (5 cm) of urethane foam with a plastic or aluminum jacket. Less costly but also less effective is Armaflex™ pipe insulation, which must be painted where it is exposed to the sun and elements. Inside the building, fiberglass or foam can be used to insulate the pipes.

Experience has shown that for best results the backup water heater tank should be bypassed when possible. Otherwise the backup water heater tank loses some of the solar heat. Obviously, bypassing the backup tank can only be done when the solar water temperature is high enough. When it is, the savings in energy is well worth the time required to switch the valves each year. Bypassing would be less important with a very well insulated backup heater tank, but you might wish to experiment even with this type of system to determine the most efficient mode of operation.

You can also improve the performance of the system by scheduling water use to fit supply. Shower, wash and launder when water is the hottest-during the afternoon or early evening.

Some IPSWH's will work so well that water temperature will be high enough to be scalding. This is a particular danger to children. For $12 to $15 a tempering valve between the heater and point of use can prevent any hazards from overly hot water.

Build It To Last

Even an inexpensive IPSWH might not provide economical solar heating if it only lasts one season-or if it leaks into the house on top of your favorite antique. It will pay you to build it to last. This will require sound construction technique, protection from corrosion, freeze protection, and, just in case, protection if leaks occur. The importance of these various elements will vary by climate, water type, and location of the heater.

Good construction will not only help your heater last longer-but will generally make it look better as well. The most common errors are made in flashing, glazing, and painting. You can avoid these by careful study, asking for advice, and attention to detail.

Flashing joints properly will prevent most weather related leaks from occurring in the IPSWH. Every joint should offer mechanical barriers to water entry (simply slopping on caulk won't do). A variety of flashing extrusions are readily available at building and solar supply stores. Choose and apply them with care.

The most common problems with glazing involve the hold down system. With plastics the error is usually failure to accommodate expansion correctly-resulting in cracks in the plastic. These can be avoided by allowing the plastic to move with oversize screw holes or clamps. With glass the more common problem is failure of the hold down strips or battens and corrosion of screws and fasteners.

You can ensure a good appearance by carefully choosing paints and preparing surfaces for painting. Make sure you have cleaned surfaces well, 'se the appropriate primer (or primers), and apply finish coats that will withstand high temperatures. Proper painting will virtually eliminate exterior corrosion and weathering.

Internal corrosion must also be reduced or prevented. Be particularly careful if a variety of materials are used in the system-if dissimilar materials are used, make sure dielectric breaks are included to reduce corrosion. I prefer to use copper as much as possible to reduce corrosion; and where it is joined to galvanized pipe or tanks I use plastic dielectric unions to prevent accelerated corrosion.

The tank or collector itself must also be protected to resist corrosion. Galvanizing alone is insufficient in most areas. With the high temperatures in the box most water is fairly corrosive and galvanized tanks may last less than two years. Glass lined or stone lined tanks are better but even they should be protected with a sacrificial anode. This anode is of a less corrosion resistant material and saves the tanks and pipes. A look at these anodes from IPSWH's in use 3 to 4 years in Davis, California revealed considerable loss of material and it might be very good practice to replace them every 3 to 5 years.

Freezing can also wreak havoc on IPSWH's although they are less sensitive than most other solar systems. Even very simple IPSWH's will survive, occasional drops to 20°F (-6.7°C) or less. Some are reputed to be safe as low as O°F (-17.8°C) or lower but more experience is needed to really predict how they will do.

The tanks' high thermal mass and movable insulation (if used) will give the system some protection from freezing. However, in colder areas some form of freeze protection will be required.

The most common method is simply draining the heater during the coldest part of the winter. Make sure it will drain completely by installing an air vent or valve to let air in to replace the water when it drains. You might also have an automatic draindown valve installed so the system will drain itself only when it gets cold. Automatic draindown would not only be less, trouble but it would also allow the system to provide heating for much of the winter.

The most sensitive part of most IPSWH installations is the piping to and from the heater-and this must be very well insulated and designed for complete drainage if drainage is to be used for freeze protection. Make sure the pipe runs consistently downhill to a drain-and drain it carefully. The connecting pipes in the heater box are also more susceptible than the tanks and should be insulated in areas where freezing may be a problem.

Other options for freeze protection have also been used and may be worth considering. In milder climates you can leave the electrical heater element in the IPSWH-and have it provide both backup heating and freeze protection. Another strategy would be a vent or door that can be opened to allow heated air from the house into the IPSWH. A gas furnace flue might also be used as a heat source.

In much colder areas the heater may need more powerful freeze protection. First consider putting the heater right in the house or greenhouse. If that isn't possible you might have to use a heat exchanger set in a freeze proof liquid filled collector tank. If a single walled heat exchanger is used then the antifreeze must be nontoxic. Propylene glycol is acceptable, ethylene glycol (car antifreeze) is not as it is highly toxic.

Phase change materials may also be used for freeze protection. These could change phase at 70°F or 80°F (21°C to 27°C) or lower and could be put in the collector box as a liner. As the heater cooled off these would give up their stored heat to keep it above freezing.

And finally, consider what can happen if something does leak (because of weather leaks, corrosion, or freezing). Put a drip pan with drain to protect the heater and the house beneath it. These are most commonly made of galvanized iron sheet with turned up edges but they could be fiberglassed wood or plastic. Bent Nail Construction used a gutter running across the bottom of the inclined tank bed in one heater to collect water from any possible leak and carry it outside. For a ground mounted heater this is not as important-but the drainpan can prevent damage to the wood box and probably should be included.

Backup Heating

In the cooler areas of the U.S. even a fairly sophisticated IPSWH with insulated lids may not provide sufficient hot water in the winter, and you will have to install some form of backup heating. The best choice for you depends on a number of factors including: availability of other sources of energy, hot water demand, climate, and your existing hot water heater.

The availability of other energy sources may by itself determine your backup system. If, for example, you use wood for your space heating, it usually makes sense to add a heat exchanger to your stove or furnace to heat water. The IPSWH tank, if insulated lids are installed, may be an excellent storage tank for your wood heated hot water. The best source of information about wood water heating is Handmade Hot Water Systems by Art Sussman and Richard Frazier.

If you have sufficient solar space heating for your home and therefore don't really need a fire often, you might elect to install a wood fired water heater. You can buy these ready made or make your own from a recycled gas water heater.

If wood is not readily available or you would prefer not to deal with it, you might choose to install more conventional electric or gas backup water heating. If heat loss is expected to be minimal-such as for mild climate IPSWH's, IPSWH's located in greenhouses or in the house, or IPSWH's with very well insulated boxes and lids-you might consider removing the existing conventional heater and adding the backup heating elements to the IPSWH itself. This will save money, free space in the house for other uses, and reduce indoor air pollution (if the conventional heater was gas).

In systems with a regular backup heater with tank, you should turn off the backup heater and bypass it when the IPSWH is providing enough heat. Experience has shown that leaving the remote storage tank full of hot water adds unnecessary losses to the system, and you are better off not doing it. Make the valving simple to understand, with color codes keyed to instructions marked on a nearby wall, or it won't be used properly when you leave or sell the house.

Another option which avoids these storage losses completely is the flash or line water heater. These are widely used in Europe and have only recently. Become more available in the U.S. These heaters use energy to heat the water as it goes through them and don't have a storage tank. Experience suggests that they may save forty percent of the energy used in a conventional heater.

Unfortunately, many of the flash heaters available today have a fixed temperature rise. That is, if the water comes in at 60°F (16°C) it goes out at 120°F (49°C). If it comes in at 140°F (60°C) it goes out at 200°F (93°C). This type of heater can be dangerous with a solar heater unless a point of use mixing value is used. This valve automatically sets the temperature by mixing cold and hot water before it comes out the faucet.

A final option worth considering is the very small, very hot water heater typified by Emerson's "Hot Tap." This one quart heater provides limited quantities of approximately 180°F (82°C) water at the sink. It makes a good booster for dishwater if the solar water is not hot enough. It is also excellent for making coffee, tea, or soup. It can be switched with a wall switch so it is on only when you will use it.

Environmental variables of solar hot water

Basics of solar energy

Since the solar water heating model deals with solar energy, some basic concepts of solar energy engineering first needs to be explained. This section does not intend to be a course on the fundamentals of solar energy; the reader interested in such topics could benefit from consulting a textbook on the subject, from which most of the equations in this section are derived. This section does intend, however, to detail the calculation of a few variables that will be used throughout the model.

Declination

The declination is the angular position of the sun at solar noon, with respect to the lane of the equator. Its value in degrees is given by Cooper's equation:

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right)$$

where n is the day of year

Solar hour angle and sunset hour angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. For example at 7 a.m. (solar time2) the solar hour angle is equal to –75° (7 a.m. is five hours from noon; five times 15 is equal to 75, with a negative sign because it is morning). The sunset hour angle ωs is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

$$\cos\omega_s = -\tan\psi \ \tan\delta$$

where δ is the declination, calculated through equation (1), and ψ is the latitude of the site, specified by the user.

Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, H0, can be computed for the day of year n from the following equation:

$$H_0 = \frac{86400 G_{sc}}{\pi}\left(1+0.033\cos\left(2\pi\frac{n}{365}\right)\right)\left(\cos\psi\cos\delta\sin\omega_s + \omega_s\sin\psi\sin\delta\right)$$

where Gsc is the solar constant equal to 1,367 W/m2 , and all other variables have the same meaning as before.

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index, K T , is defined as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0}$$

Tilted irradiance

Solar radiation in the plane of the solar collector is required to estimate the efficiency of the collector (Section 2.2) and the actual amount of solar energy collected (Sections 2.3 and 2.4). The RETScreen SWH Project Model uses Liu and Jordan's isotropic diffuse algorithm to compute monthly average radiation in the plane of the collector, HT :

$$\bar{H}_T = \bar{H}_b\bar{R}_b + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{H}\ \rho_g\left(\frac{1-\cos\beta}{2}\right)$$

The first term on the right-hand side of this equation represents solar radiation coming directly from the sun. It is the product of monthly average beam radiation Hb times a purely geometrical factor, Rb , which depends only on collector orientation, site latitude, and time of year3 . The second term represents the contribution of monthly average diffuse radiation, Hd , which depends on the slope of the collector, β. The last term represents reflection of radiation on the ground in front of the collector, and depends on the slope of the collector and on ground reflectivity, ρg. This latter value is assumed to be equal to 0.2 when the monthly average temperature is above 0°C and 0.7 when it is below -5°C; and to vary linearly with temperature between these two thresholds.

Monthly average daily diffuse radiation is calculated from global radiation through the following formulae:

1. for values of the sunset hour angle ωs less than 81.4°:

$$\frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137K_T^3$$

2. for values of the sunset hour angle ωs greater than 81.4°:

$$\frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821K_T^3$$

3. The monthly average daily beam radiation Hb is simply computed from:

$$\bar{H}_b = \bar{H} - \bar{H}_d$$

Related research papers

Young-Chae Song, et al. (2004). Studied the performance of thermophilic and mesophilic temperature co-phase anaerobic digestions for sewage sludge, using the exchange process of the digesting sludge between spatially separated mesophilic and thermophilic digesters, was examined, and compared to single-stage mesophilic and thermophilic anaerobic digestions. The reduction of volatile solids from the temperature co-phase anaerobic digestion system was dependent on the sludge exchange rate, but was 50.7–58.8%, which was much higher than 46.8% of single-stage thermophilic digestion, as well as 43.5% of the mesophilic digestion. The specific methane yield was 424–468 mL CH_4 per gram volatile solids removed, which was as good as that of single-stage mesophilic anaerobic digestion. The process stability and the effluent quality in terms of volatile fatty acids and soluble chemical oxygen demand of the temperature co-phase anaerobic digestion system were considerably better than those of the single-stage mesophilic anaerobic processes. The destruction of total coliform in the temperature co-phase system was 98.5–99.6%, which was similar to the single-stage thermophilic digestion. The higher performances on the volatile solid and pathogen reduction, and stable operation of the temperature co-phase anaerobic system might be attributable to the well-functioned thermophilic digester, sharing nutrients and intermediates for anaerobic microorganisms, and selection of higher substrate affinity anaerobic microorganisms in the co-phase system, as a result of the sludge exchange between the mesophilic and thermophilic digesters.

Ahn J-H. and Forster C.F. (2002). A study was carried out to assess the effect of temperature variations, both decreasing and increasing, on the performance of a mesophilic (35°C) and a thermophilic (55°C) upflow anaerobic filter treating a simulated papermill wastewater. An organic loading rate of 1.95 kg COD per m3 day was used throughout the study. The temperature of the mesophilic digester (MD) was lowered to room temperature (18–24°C) for 11 days and then returned to 35°C. The temperature of the thermophilic digester (TD) was lowered to 45°C for the 11 days followed by a further decrease to 35°C for 6 days. It was then returned to 55°C. To examine the effect of an increase in temperature, the temperature of the MD was raised to 45°C for 6 days, followed by an increase to 55°C for 5 days and that in the TD was raised to 65°C for 11 days. The mesophilic digester was affected by the drop in temperature but the TD only showed a marked reaction when the temperature was lowered to 35°C. The temperature decrease caused lower COD removal efficiencies, higher suspended solids (SS) in the effluent, lower biogas production, and accumulation of volatile fatty acids (VFA). However, both reactors were able to recover their efficiencies fully after the temperatures readjusted to their optimum temperature conditions. The temperature increase to 45°C in the MD did not show any detrimental effect, while the temperature increases to 55 and 65°C in MD and TD, respectively, gave immediate drops in the treatment efficiency. However, it appeared that the bacteria in both digesters were able to adapt to the higher temperature after a few days acclimatisation to the temperature shock. After the temperatures readjusted to their optimum temperature conditions, thermophilic microorganisms appeared to be more resilient to the temperature increase than mesophilic microorganisms.

Kaparaju P. and Angelidaki I. (2008). The objective of the study was to identify the optimum time interval for effluent removal after temporarily stopping stirring in otherwise continuously stirred tank reactors. Influence of temperature (10 and 55°C) and active biogas process on passive separation of digested manure, where no outside mechanical or chemical action was used, within the reactor was studied in three vertical settling columns (100 cm deep). Variations in solids and microbial distribution at top, middle and bottom layers of column were assessed over a 15 day settling period. Results showed that best solids separation was achieved when digested manure was allowed to settle at 55°C with active biogas process (pre-incubated at 55°C) compared to separation at 55°C without active biogas process (autoclaved at 120°C, for 20 min) or at 10°C with active biogas process. Maximum solids separation was noticed 24 h after settling in column incubated at 55°C, with active biogas process. Microbiological analyses revealed that proportion of Archaea and Bacteria, absent in the autoclaved material, varied with incubation temperature, time and sampling depth. Short rod shaped bacteria dominated at 55°C, while long rod shaped bacteria dominated at 10°C. Methanosarcinaceae were seen more abundant in the surface layer at 55°C while it was seen more common in the top and bottom layers at 10°C. Thus, passive separation of digester contents within the reactor can be used effectively as an operating strategy to optimize biogas production by increasing the solids and biomass retention times. A minimum of 1–2 h ‘‘non-stirring’’ period appears to be optimal time before effluent removal in plants where extraction is batch-wise 2–4 times a day.

Bouallagui H., et al. (2003). Studied a semi-continuously mixed mesophilic tubular anaerobic digester was tested for the conversion of fruit and vegetable waste (FVW) into biogas. The effect of hydraulic retention time (HRT) and the feed concentration on the extent of the degradation of the waste was examined. Varying the HRT between 12 and 20 days had no effect on the fermentation stability and pH remained between 6.8 and 7.6, but an inhibition of methanogenic bacteria was observed at HRT below 12 days. The overall performance of the reactor was depressed by changing the feed concentration from 8% to 10% TS (dry weight). By applying a feed concentration of 6% and HRT of 20 days in the tubular digester, 75% conversion efficiency of FVW into biogas with a methane content of 64% was achieved.

Forster-Carneiro T., et al. (2008). Studied the influence of different organic fraction of municipal solid wastes during anaerobic thermophilic (55°C) treatment of organic matter was studied in this work: food waste (FW), organic fraction of municipal solid waste (OFMSW) and shredded OFMSW (SH_OFMSW). All digester operated at dry conditions (20% total solids content) and were inoculated with 30% (in volume) of mesophilic digested sludge. Experimental results showed important different behaviours patterns in these wastes related with the organic matter biodegradation and biogas and methane production. The FW reactor showed the smallest waste biodegradation (32.4% VS removal) with high methane production (0.18 LCH4/gVS); in contrast the SH_OFMSW showed higher waste biodegradation (73.7% VS removal) with small methane production (0.05 LCH4/g VS). Finally, OFMSW showed the highest VS removal (79.5%) and the methane yield reached 0.08 LCH4/g VS. Therefore, the nature of organic substrate has an important influence on the biodegradation process and methane yield. Pre-treatment of waste is not necessary for OFMSW.

John Gelegenis, et al. (2007). Studied Optimization of biogas production from olive-mill wastewater (OMW) was attempted by codigesting with diluted poultry-manure (DPM) at mesophilic conditions. A series of laboratory experiments were performed in continuously-operating reactors, fed with mixtures of OMW and DPM at various concentrations. It was concluded that codigestion of OMW with DPM is possible without any dilution of OMW or addition of any chemicals. Biogas production was slightly higher when OMW was added to DPM up to a critical concentration (about 40%, expressed as contribution of OMW to the volatile solids of the mixture), after which production is decreased. The results were further verified by scaling up to a continuously-operating pilot-plant reactor digesting DPM, and confirmed that no negative impact was imposed by adding OMW up to the above critical value.

Kanokwan Boe, et al. (2009). The effect of post-digestion temperature on a lab-scale serial continuous-flow stirred tank reactor (CSTR) system performance was investigated. The system consisted of a main reactor operated at 55°C with hydraulic retention time (HRT) of 15 days followed by postdigestion reactors with HRT of 5.3 days. Three post-digestion temperatures (55°C, 37°C and 15°C) were compared in terms of biogas production, process stability, microbial community and methanogenic activity. The results showed that the post-digesters operated at 55°C, 37°C and 15°C gave extra biogas production of 11.7%, 8.4% and 1.2%, respectively. The post-digester operated at 55°C had the highest biogas production and was the most stable in terms of low VFA concentrations. The specific methanogenic activity tests revealed that the main reactor and the post-digester operated at 55°C and 37°C had very active acidogens and methanogens. In contrast, very low methanogenic activity was observed at 15°C.

Biswas J., et al. (2007). Studied mathematical modeling for the prediction of biogas generation characteristics of an anaerobic digester based on food/vegetable residues An anaerobic digester of 10 L capacity has been operated in batch mode at an optimum temperature of 40°C and at a pH of 6.8 using vegetable /food residues as the feed material. The effect of slurry concentration and that of the concentration of carbohydrate, protein and fat in the slurry on the biogas production rate and methane concentration in the biogas have been studied. The slurry concentration has been varied in the range of 72.0–700 kgm^{-3}. At a slurry concentration of 67.7 kgm^{-3} the effect of carbohydrate concentration has been studied by varying the ratios of carbohydrate, protein and fat in the range of 6.9:4.3:1–12.1:4.3:1 by using a sole carbohydrate source, namely sucrose. The effect of protein concentration has been studied by varying the ratios of carbohydrate, protein and fat in the range of 5.6:7.0:1–5.6:13.0:1 by using a sole protein source, namely papain and that of fat concentration has been studied by varying the ratios of carbohydrate, protein and fat in the range of 7.2:10:1.6–7.2:10:5 by using a fat source, namely vanaspati. A deterministic mathematical model using differential system equations have been developed and it is capable of predicting the behaviour of the digester satisfactorily.

Raheman H. (2002). This paper describes the development of a mathematical model for determining the dimensions of a fixed dome type Deenbandhu model biogas plant, the most popular model constructed in India. The developed model could estimate the different dimensions within an absolute variation of 6%. This will help the designers to determine the dimensions of various capacities of a Deenbandhu model biogas plant for different hydraulic retention times to suit the local climatic conditions.

CHAPTER III

RESEARCH METHODOLOGY

In this study, the organic fraction of NU solid wastes was collected for biological treatment by anaerobic digestion process as a part of solid waste management strategies. The research was conducted on lab scale digester. The wastes for the feedstock were collected from NU cafeteria. After collecting the wastes, the manual part of the easily degradable organic fractions was carried out from the garbage. The collected wastes were fed into the shredder to obtain the average particle size of 10 mm. The inoculums were merged to the shredded small sized waste particles to increase the start-up of the digestion process. To control the bacteria and reduce the digestion period the experiment was carried in thermophilic condition and mesophilic condition.

Materials

The system of temperature control system development for biogas production consists of 2 parts as below:

1. Biogas system
2. Hot water system

Biogas system

The bioreactor had a working volume of 70 L. It consists of 2 tanks as below acid digester tank and methane digester tank. Acid digester tank was 35 L (an internal diameter of 30 cm and height of 50 cm). And methane digester tank was 35 L (an internal diameter of 30 cm and height of 50 cm) The methane digester tank was double wall container to provide hot water bath in order to maintain the temperature inside the digester. The storage tank was 75 L. (an internal diameter of 40 cm and height of 60 cm). The methane digester tank wrap with glass wool of 5 cm thickness. In bioreactor install the agitator for mix food waste and inoculums. The agitator had a working volume of 30 minutes/ hour. The speed of motor was 15 cycle /minute.

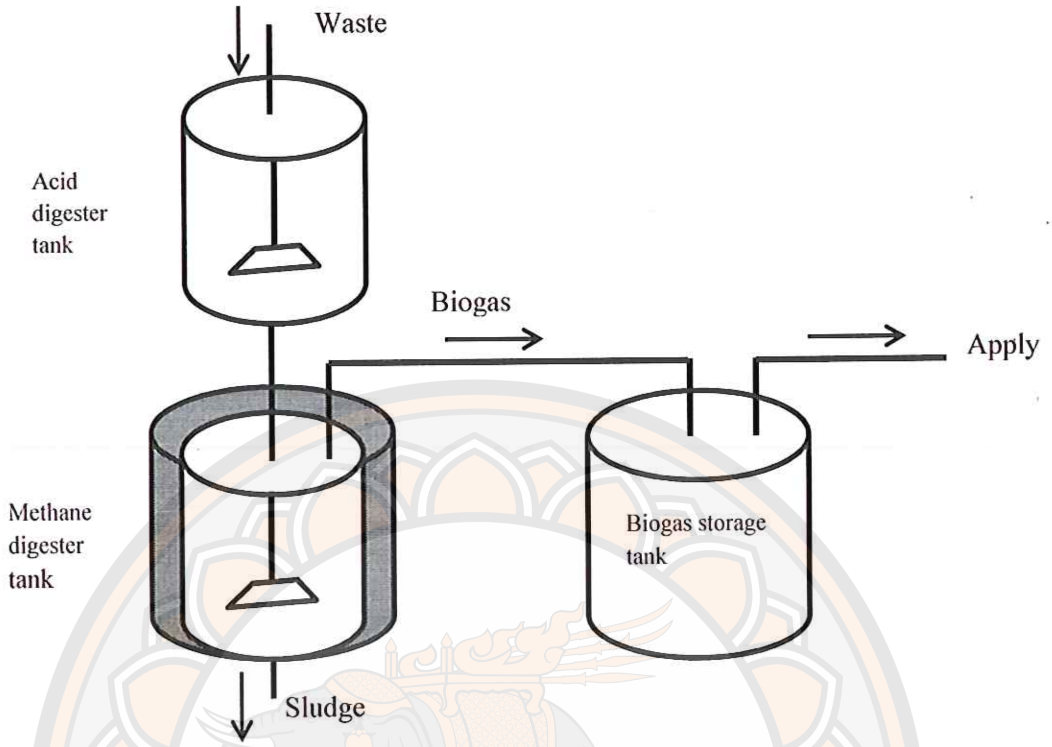

Figure 45 Anaerobic digestion systems

Hot water system

The heating required for the bioreactor was performed using a solar collector combined with biogas energy. Water contained within the jacket of the bioreactor was 35 L. Heating this volume of water to 35-60°C for the solar collector design.

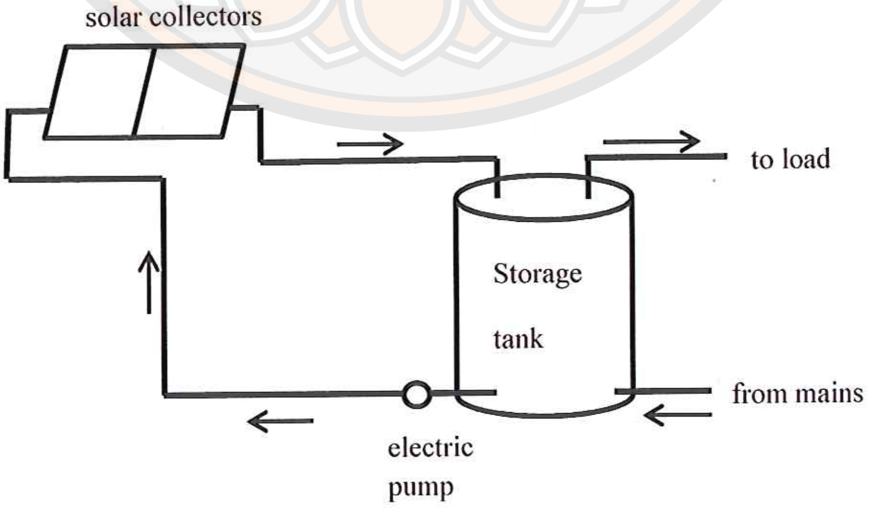

Figure 46 Solar hot water systems

Lab scale digestion system

Design of the digester

The digester was designed according to the organic loading rate and the retention time. The two stage anaerobic digestion was operated at different organic loading rates to optimize the biogas production and to research operational parameters. The digester was cylindrical with double wall container to provide hot water bath in order to maintain the temperature inside the digester.

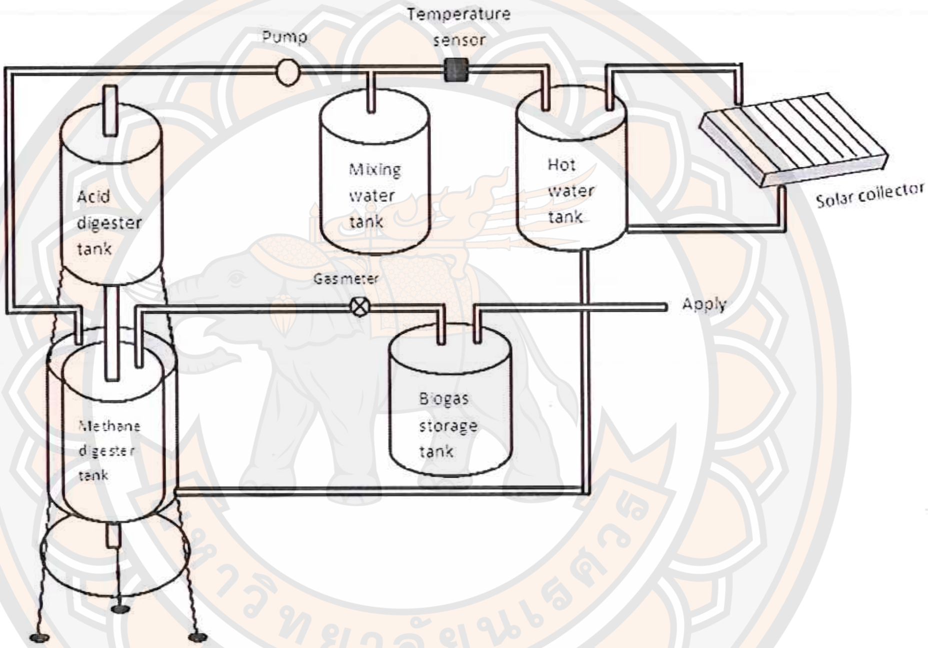

Figure 47 Design of lab scale anaerobic digestion systems

Volume of water

$$V = \frac{m_{water}}{\rho} \qquad \text{Eq.1}$$

where V = volume

m_{water} = mass of water

ρ = density

Heat energy

$$Q = m\, c_p \,\triangle T \qquad \text{Eq.2}$$

Where; Q = heat energy

m = mass

c_p = specific heat

$\triangle T$ = change in temperature (final - initial temp)

Experimental procedure

Feedstock composition

The solid wastes from NU cafeteria were used as substrate for the AD system. The compositions of which were determined by solid wastes analysis techniques. Accordingly the representative wastes were collected and the weights of wastes were reduced to sample size of 50-100 kg. The feedstock was comprises of food wastes.

Feedstock preparation

After manual sorting of the wastes material it was converted into averages size of about 10 mm by using shredder. The surface area is more at the smaller size and the hydrolysis process happen faster which is the limit factor of the methane formation in anaerobic digestion. Fresh wastes were mixed with the inoculums to enlarge the start-up process and were fed into the digester based upon the organic loading rate.

Inoculums

Inoculum source is a very important operational parameter. Also, it is decisive the selection of waste/inoculum ratio as well as the assessment of anaerobic biodegradability of solid wastes. The percentage of inoculation for acid organic fermentation of organic urban wastes is approximately 30% (w/w). Cow dung, digestion material, anaerobic sludge was used as inoculums components. The constituent of inoculums was cow dung, anaerobic sludge and digestion material in the ratio of 2:1:1. The purpose of using these mixtures was to increase the microbial diversity inside the reactor.

Sampling and analytical procedure

The analysis in this study was made for feedstock, digestion and biogas produced. The parameters to be analyzed for feedstock and digestion were Moisture Content (MC), TS, and VS. These parameters were used to compare the system performances and were controlled to provide the stability of the system. All analytical determinations were performed according to "Standard Methods". In addition to above mentioned operational parameters, nutrients (nitrogen, phosphorus, potassium, carbon) in the new wastes and digestion were also analysis.

Solid waste analysis

Both new waste and digested waste were subjected to solid analysis. Solid waste analysis was conducted before feeding into the digester and after withdrawing the digestion from digester. Representative grab sample of Solid waste were collected and were analyzed for parameters such as moisture content, TS, VS and bulk density.

Moisture content

The percent moisture of the MSW samples was determined by weighing 100 g of the samples into a pre-weighed dish and drying the samples in an oven at 105°C for 24 hours to a constant weight. The percent MC and TS were calculated using Eq.3 and 4. The analysis was conducted in duplicates. After determining the moisture content, the samples were further tested for volatile matter content as explained in the section that follows.

$$\%\,\text{MC} = \left(\frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Wet Weight}}\right)\times 100\% \qquad \text{Eq.3}$$

$$\%\text{TS} = 100\% - \%\text{MC} \qquad \text{Eq.4}$$

Volatile solid

The volatile solid content was determined by the method of ignition of the sample at 550°C for 1 hour. The same sample as was determined for moisture content and total solid was used for determining volatile solids. The dried samples were pulverized into fine solids and were mixed properly to ensure homogeneity. After that the pulverized sample were weighed for 2 g. and were placed on several crucible dishes. Then the sample was evaporated for at least 1 hour at 550°C in the muffle furnace. After drying the sample was placed into desiccator for cooling and was weighed immediately by using analytical balance. Thus volatile solid was calculated using Eq.5.

$$\%\,\mathrm{VS} = \frac{w_o - w_f}{w_o - w_f} \times 100\% \qquad \text{Eq.5}$$

Where w_0 = weight of sample and evaporating dish after 105°C

w_f = weight of sample and crucible dish after 550°C

w_e = weight of empty dish

Total solids and Volatile solids loss

The feedstock entering into the digester for AD process has an incipient total wet weight of TW_0 and dry mater M_0. The residue for the overall process has the final total weight of TW_1 and dry matter M_1.Total solid loss can be determined by using Eq.6. The Eq.7 gives the dry weight of material before feeding into the digester whereas Eq.8 depicts the dry weight of digestion. For calculating the loss of volatile solid, Eq.9 can be used similarly Eq.10 and 11 represents the amount of volatile solids in the feedstock and digestion respectively.

The following equations were used to obtain percentage of total solid (%TS) loss and percentage of volatile solids (%VS) loss.

$$\%\,\mathrm{TS} = \frac{M_0 - M_1}{M_0} 100\% \qquad \text{Eq.6}$$

Where M_0 = dry weight of feedstock entering into the reactor, (g)

$$M_0 = TW_0 \times TS_0$$ Eq.7

Where TW_0 : wet weight of solid wastes entering into the reactor, (g)

TS_0 : percentage total solid of feedstock (%TS)

M_1 : dry weight of digestion extracting from reactor, (g)

$$M_1 = TW_1 \times TS_1$$ Eq.8

Where TW_1 : wet weight of digestion extracting from the reactor, (g)

TS_1 : percentage total solid of digestion (%TS)

$$\% VS = \frac{N_0 - N_1}{N_0} \times 100\%$$ Eq.9

Where N_0 = weight of volatile solids entering into the reactor, (g)

$$N_0 = M_0 \times VS_0$$ Eq.10

Where VS_0 : percentage volatile solid of feedstock (%TS)

N_1 : weight of volatile solid of digestion extracting from reactor, (g)

$$N_1 = M_1 \times VS_1$$ Eq.11

where VS_1 : percentage volatile solid of digestion (%TS)

Table 18 Solid waste characteristics of fresh waste

Parameters	Units	Fresh waste
pH		4.38
Total wet weight	L	20
Moisture content (MC)	%	93.8
Total Solids (TS)	%	6.25
Total Volatile Solids (TVS)	kg	5.56
Chemical oxygen demand (COD)	mg/l	43,520
Nutrient analysis		
N	%	0.08
P	mg/l	7.87
K	%	0.04
C	%	0.169
C/N	%	0.17/0.08

Biogas analysis

To measure the performance of AD process, the biogas produced was observed daily. Gas samples were taken from the headspace of the bioreactors by a syringe with pressure lock. The sample was injected directly into the Gas Chromatograph install thermal conductivity sensor for analysis volume composition of biogas (CH_4, CO_2 and other gas).

Economics analysis

The cost of producing biogas is one of the common tools used to evaluate the viability of an energy system. The cost is the investment of the system in total lifetime costs of the energy system divided by the quantity of energy produced over the system lifetime. When considering the systems, capital cost of digester and solar hot water system, operation and maintenance cost of the digester and solar hot water system, and fuel cost.

Capital cost of building the system; yearly calculate

C_C = Capital cost of building the system (CRF, i, n) Eq.12

C_C = Capital cost of building the system $\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$

Where i = Interest rate (%)

n = Number of years (year)

Investment cost of the system; yearly calculate

C_C = Cost of the system (CRF, i, n) Eq.13

C_C = Cost of the system $\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$

Ruins value of the system; yearly calculate

C_S = Ruins value of the system (SFF, i, n) Eq.14

C_S = Ruins value of the system $\left[\frac{i}{(i+1)^n-1}\right]$

Expenses cost of fuel per year

C_F = (Cost of fuel x Rate of fuel consumption)
x (Hour operating per year) Eq.15

Expenses cost of electricity per year

C_E = (Power electric value per unit x Power electric for using)
x (Hour operating per year) Eq.16

Maintenance per year

$$C_M = 5\% \text{ of capital cost of building the system} \qquad \text{Eq.17}$$

Yearly total expenses cost

$$C_T = C_C + C_F + C_E + C_M - C_S \qquad \text{Eq.18}$$

Total expenses cost per rate of system production

$$\text{Total expenses cost per rate of system production} = \frac{\text{Yearly total expenses cost}}{\text{Rate of system production yearly}} \qquad \text{Eq.19}$$

Expenses cost operating yearly

$$C_O = C_F + C_M + C_E \qquad \text{Eq.20}$$

Expenses cost operating per rate of system production

$$\text{Expenses cost operating per rate of system production} = \frac{\text{Yearly expense cost operating}}{\text{Rate of system production yearly}} \qquad \text{Eq.21}$$

Payback period

$$\text{Payback period} = \frac{\text{Capital cost of building the system}}{\text{Reward net per year}} \qquad \text{Eq.22}$$

CHAPTER IV

RESULTS

This section describes the results obtained during the lab-scale anaerobic digestion of food waste operating in thermophilic condition and mesophilic condition. The experiments were conducted in two-stage anaerobic digestion system i.e. acid phased digestion and methane phased digestion. The analysis and evaluation are described to examine the performance in laboratory-scale experiment to achieve the objectives of this study.

The biogas production at various temperatures digestion

The biogas production at various temperatures digestion

Biogas from the degradation of food waste as a renewable source of energy is presented in Figure 48. The data shown are the biogas generation from reactors incubated at mesophilic temperature (20-40°C) and thermophilic temperature (50-65°C). Maximum biogas production occurred at 55°C (38.14 L. of biogas) when compared to the other temperatures. Second best was at 50°C (37.44 L. of biogas), followed by 40°C (35.36 L. of biogas) respectively (the detail are attached in Appendix D).

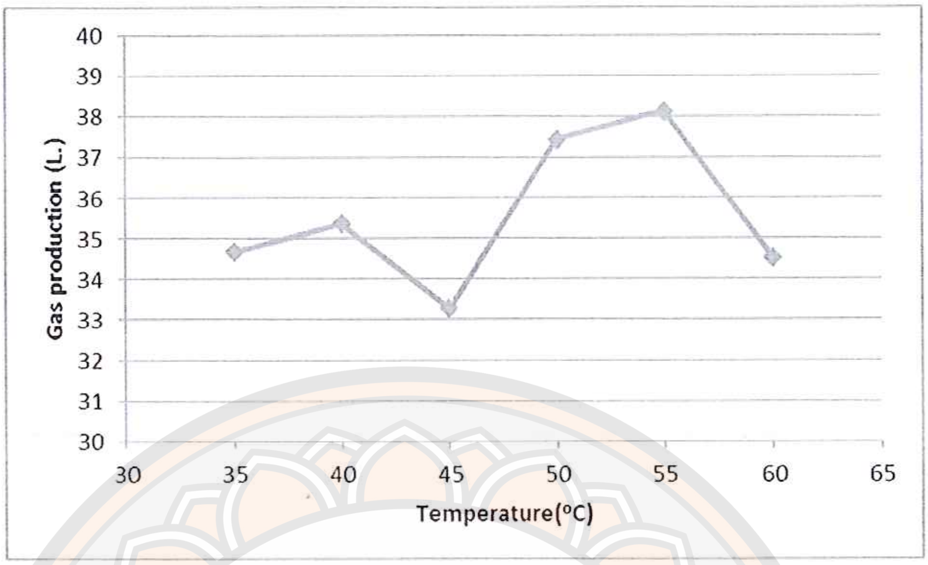

Figure 48 Biogas production (L.) at various temperatures digestion

The biogas composition at various temperatures digestion

The biogas composition of the biogas production from reactor incubated at mesophilic temperature is presented in Figure 49. The data shown that the biogas composition from reactors incubated at 40°C. Maximum methane of the biogas production was 57%. Second carbon dioxide was 35%, followed other gas was 8% respectively.

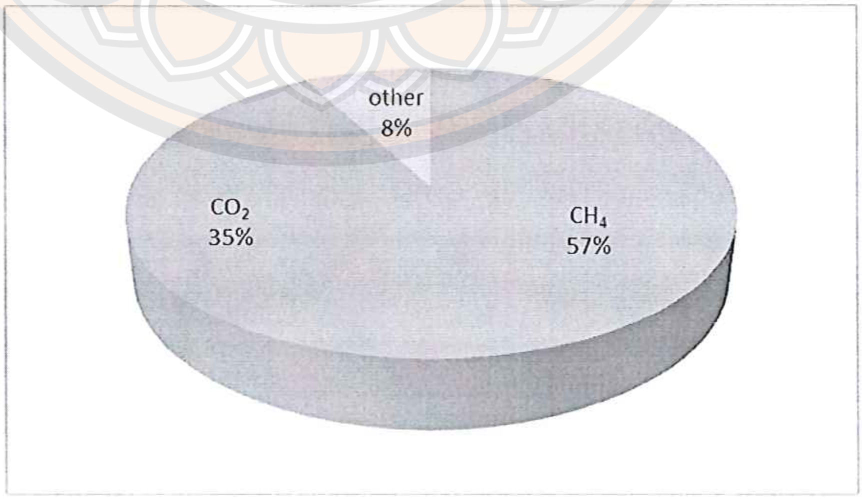

Figure 49 Biogas composition occurred at 40°C

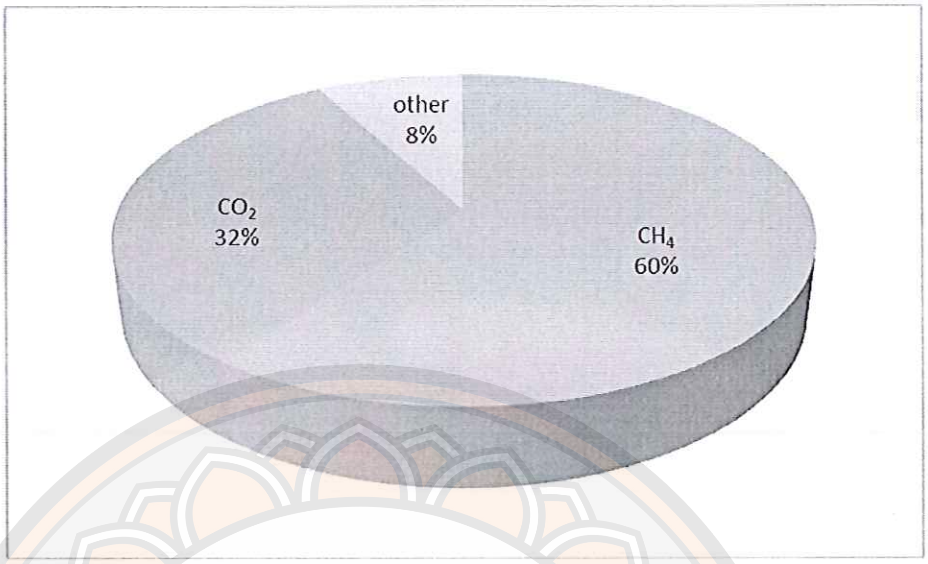

Figure 50 Biogas composition occurred at 55°C

The biogas composition of the biogas production from reactor incubated at thermophilic temperature is presented in Figure 50. The data shown that the biogas composition from reactors incubated at 55°C. Maximum methane of the biogas production was 60%. Second carbon dioxide was 32%, followed other gas was 8% respectively.

Time digestion at various temperatures digestion

The day digestion of the biogas production is presented in Figure 51. The data shown are the days digestion from reactors incubated at mesophilic temperature (20-40°C) and thermophilic temperature (50-65°C). Minimum day digestion of the biogas production occurred at 55°C (11 days) when compared to the other temperatures. Second best was at 50°C (12 days), followed by 35 and 40°C (15 days) respectively. This lower days digestion, when compared to the other temperatures, is attributed to a temperature of about 55°C is important for bacteria's growth and activity.

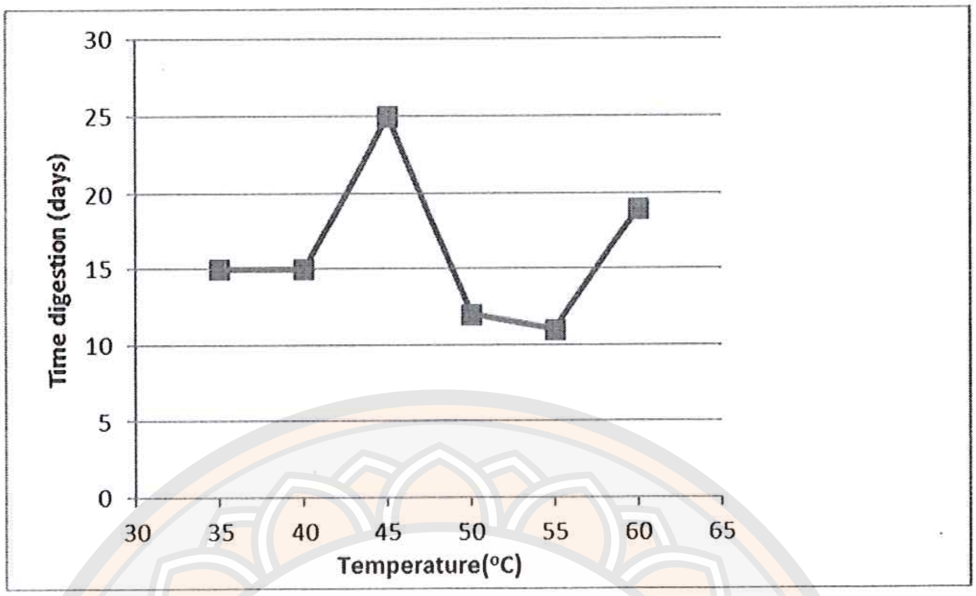

Figure 51 **Time digestion (days) at various temperatures digestion**

The results of the laboratory-scale experiment, maximum biogas production occurred at 55°C (38.14 L. of biogas) for a period of 11 days when compared to the other temperatures. Second best was at 50°C (37.44 L. of biogas) for a period of 12 days, followed by 40°C (35.36 L. of biogas) for a period of 15 days respectively.

Develop the temperature control system for biogas production.

In solar hot water system design, it is necessary to estimate the long-term average heating load. The hot water load or the amount of the energy required to warm water from the inlet cold water temperature to a desired temperature is dependent on several factors such as cold water inlet temperature, location, system characteristic and quality. This load also includes any heat loss from the storage tank and piping system.

Solar heating

The heating required for the bioreactor was performed using a solar collector combined with biogas energy. Water contained within the jacket of the bioreactor was 35 liters and the bioreactor volume was 70 liters. Heating this volume of water to 35-60°C for the solar collector design.

Solar collector

The solar collector consists of a galvanized steel flat plate of 4.98 m^2 dimensions. The absorber was insulated with a glass wool layer of 4 cm thickness at the bottom. All of these parts were arranged within a box of galvanized steel base and glass top.

Controller

Heating the bioreactor using solar energy can be approximated by first order dynamics. Since solar energy radiation is continuously affect the system, a closed loop controller has to be used over an open loop controller.

Two types of controllers were implemented; an on–off controller, and an analog PID controller. The on–off controller sensor was sensitive to small temperature variations. It responded to temperature error before it was switched to an on–off position. Other reasons using a PID controller are due to the sensitivity of the controller to input variation and the simplicity of the parameters design.

Design of solar collector by calculations

The bioreactor volume is 70 liters and the water contained within the water jacket is 35 liters. The flow rate of water was 15 liters /hour (force circulation) and 1°C temperature difference between the water jacket inlet and outlet. Heating this volume of water to 35-60°C for the solar collector design. Temperature of water inlet was 30°C.

Solar radiation was 18,200 kJ. / m^2/ day.

Efficiency of flat plate solar collector 0.5

$$= 18,200 \times 0.5 \text{ kJ./m}^2 \text{/day}$$

$$= 9,100 \text{ kJ./m}^2 \text{/day}$$

Heat to water

$$Q = m\, c_p \triangle T$$

Flow rate of water was 15 liters /hour.

Working hour of hot water was 24 hours/day.

Total hot water was 360 liters /day.

Specific gravity of water was 1 liter per 1 kilogram.

Flow rate of water was 360 liters / kilogram.

specific heat of water was 4.2 kJ/kg °C.

$$Q = (360 \text{ kg})(4.2 \text{ kJ/kg °C})(60 - 30) \text{ °C}$$
$$= 45{,}360 \text{ kJ}$$

$$\text{Size of flat plate solar collector} = 45{,}360 \text{ kJ} / 9{,}100 (\text{kJ/m}^2)$$
$$= 4.98 \text{ m}^2$$

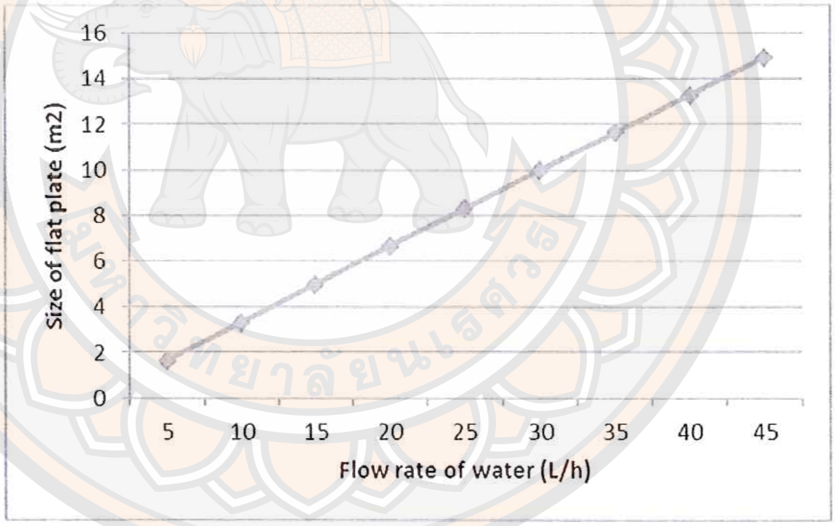

Figure 52 The size of flat plate (m^2) at flow rate water (L/h)

When increase the size of the biogas system need to increase the flow rate of water. Therefore, in order to temperature constant need to increase the size of flat plate. In Figure 52, the data shown are the size of flat plate from flow rate water in 24 hours operation by the calculation.

The water contained within the water jacket was 35 liters.

The flow rate of water was 15 liters /hour (0.004 L / second)

The time of water flows out = 35 /15

= 2.4 hours.

Heat losses rate of hot water

$Q = m^{o}\, c_p\, \triangle T$

$= (0.004\ \text{kg/s})\ (4.2\ \text{kJ/kg}\ ^{o}\text{C})\ (1\ ^{o}\text{C})$

$= 0.0168\ \text{kJ/s}$

$= 16.8\ \text{watt}$

$Q_{loss} = (2.4\ \text{h}) \times (16.8\ \text{watt})$

$= 145{,}152\ \text{watt}$

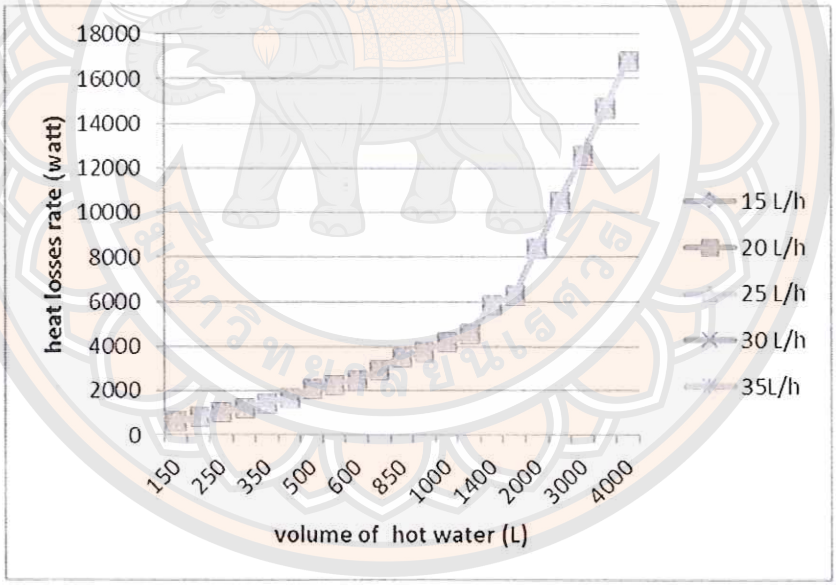

Figure 53 The heat losses rate (watt) at volume of hot water

When increase the size of the system need to increase the volume of hot water. Therefore the heat losses rate increase. In Figure 53, the data shown are the heat losses rate from volume of hot water by the calculation.

If the temperature of hot water was reaction at 60 °C and the system needed to be mixing at the temperature of 40 °C then the 30 °C water was used to mix of 70 L by the calculate was shown.

Q_{hot} = Q_{cool}
Energy balance $M \cdot c_p \triangle T$ = $X \cdot c_p \triangle T$
(35L) (4.2 kJ/kg °C) (60-40) = X (4.2 kJ/kg °C) (40-30)
2940 = 42X
X = 70 L

If the temperature of hot water was reaction at 60 °C and the system needed to be mixing at the temperature of 55 °C then the 30 °C water was used to mix of 7 L by the calculate was shown.

Q_{hot} = Q_{cool}
Energy balance $M \cdot c_p \triangle T$ = $X \cdot c_p \triangle T$
(35L) (4.2 kJ/kg °C) (60-55) = X (4.2 kJ/kg °C) (55-30)
735 = 105X
X = 7 L

specific heat of biogas was 1.6 kJ/kg °C.

If the temperature of hot water was reaction at 35 °C and the system needed to be mixing at the temperature of 40 °C then the biogas burn of water to mix of 91.88 kJ by the calculate was shown.

Q_{hot} = Q_{cool}
Energy balance $M \cdot c_p \triangle T$ = $X \cdot c_p \triangle T$
(35L) (4.2 kJ/kg °C) (40-35) = X (1.6 kJ/ kg °C) (40-35)
735 = 8X
X = 91.88 kJ

If the temperature of hot water was reaction at 55 °C and the system needed to be mixing at the temperature of 40 °C then the biogas burn of water to mix of 91.88 kJ by the calculate was shown.

$$\begin{aligned}
Q_{hot} &= Q_{cool} \\
\text{Energy balance } M\cdot c_p \triangle T &= X\cdot c_p \triangle T \\
(35L)\,(4.2\ \text{kJ/kg}\,^{\circ}\text{C})\,(55\text{-}35) &= X\,(1.6\ \text{kJ/ kg}\,^{\circ}\text{C})\,(55\text{-}35) \\
2{,}940 &= 32X \\
X &= 91.88\ \text{kJ}
\end{aligned}$$

Analysis the economic parameter

Economics analysis in this research will be study temperature control system for biogas production cost that the economics analysis consist of evaluation expenses side the other yearly both biogas production system and find out payback period in case.

Assumption and parameter for evaluation economic analysis consist of;

1. The capital cost of building the system.
    1.1 Biogas system 8,000 Bath.
    1.2 Hot water system 90,000 Bath. (data: September 2014)
2. Discount rate 7.5%.
3. Total hour of operating system 8,400 hour/year.
4. Maintenance cost 5% of the system.
5. The cost of electricity 3.5 Baht/kWh.
6. Ruins value of the system 10% of the capital cost of building the system.
7. In term of payback period analysis the reward net per year will be compared the cost of maintenance.

Capital cost of building the system (biogas); yearly calculate

C_C = Capital cost of building the system (CRF, i, n)

$C_{C\text{-biogas}}$ = Capital cost of building the system $\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$

= $8{,}000\left[\frac{7.5\%(1+7.5\%)^5}{(1+7.5\%)^5-1}\right]$

= 1,976 Baht /year

Investment cost of building the system (solar hot water); yearly calculate

$C_{C\text{-hot water}}$ = Cost of the system $\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$

= $90{,}000\left[\frac{7.5\%(1+7.5\%)^5}{(1+7.5\%)^5-1}\right]$

= 22,230 Baht /year

Ruins value of the system (biogas); yearly calculate

C_S = Ruins value of the system (SFF, i, n)

$C_{S\text{-biogas}}$ = Ruins value of the system $\left[\frac{i}{(i+1)^n-1}\right]$

= $8{,}000\left[\frac{7.5\%}{(7.5\%+1)^5-1}\right]$

= 1,376 Baht /year

Ruins value of the system (solar hot water); yearly calculate

$C_{S\text{- hot water}}$ = Ruins value of the system $\left[\frac{i}{(i+1)^n-1}\right]$

= $90{,}000\left[\frac{7.5\%}{(7.5\%+1)^5-1}\right]$

= 15,480 Baht /year

Maintenance (biogas) per year

$C_{M\text{-biogas}}$ = 5% 0f capital cost of building the system

= 8,000 x 5%

= 400 Baht /year

Maintenance (solar hot water); per year

$C_{M\text{-hot water}}$ = 5% 0f capital cost of building the system

= 90,000 x 5%

= 4,500 Baht /year

Expenses cost fuel per year

C_F = (Cost of fuel x Rate of fuel consumption) x (Hour operating per year)

= 0 Baht /year

Expenses cost electricity per year

C_E = (Power electric value per unit x Power electric for using) x (Hour operating per year)

= 3.5 Baht/unit x o.4 kW x 8,400 hour/year

= 11,760 Baht /year

Yearly total expenses cost

C_T = $C_{C\text{-biogas}} + C_{C\text{-hot water}} + C_{M\text{-biogas}} + C_{M\text{-hot water}} + C_F + C_E - C_{S\text{-biogas}} - C_{S\text{- hot water}}$

= 1,976 + 22,230 + 400 + 4,500 + 0 + 11,760 -1,376 - 15,480

$= 24{,}010 \text{ Baht /year}$

Total expenses cost per rate of system production

$$\text{Total expenses cost per rate of system production} = \frac{\text{Yearly total expenses cost}}{\text{Rate of system production yearly}}$$

$$= \frac{24{,}010 \text{ Baht /year}}{3.47 \text{ L/day} \times 350 \text{ days}}$$

$$= \frac{24{,}010 \text{ Baht /year}}{1{,}214.50 \text{ L/year}}$$

$$= 19.77 \text{ Baht / L}$$

Expenses cost operating yearly

$$C_O = C_F + C_{M\text{-biogas}} + C_{M\text{-hot water}} + C_E$$

$$= 0 + 400 + 4{,}500 + 11{,}760$$

$$= 16{,}660 \text{ Baht /year}$$

Expenses cost operating per rate of system production

$$\text{Expenses cost operating per rate of system production} = \frac{\text{Yearly expense cost operating}}{\text{Rate of system production yearly}}$$

$$= \frac{16{,}660 \text{ Baht /year}}{1{,}214.50 \text{ L/year}}$$

$$= 13.72 \text{ Baht / L}$$

Payback period

$$\text{Payback period} = \frac{\text{Capital cost of building the system}}{\text{Reward net per year}}$$

$$= \frac{8{,}000 + 90{,}000 \text{ Baht}}{400+4{,}500+11{,}760 \text{ Baht/year}}$$

$$= 5.88 \text{ year}$$

Payback period (free the hot water system)

$$= \frac{8{,}000 \text{ Baht}}{400+11{,}760 \text{ Baht/year}}$$

$$= 0.66 \text{ year}$$

Payback period of temperature control system for biogas production system was 5.88 year. Consideration total expenses cost per rate of system production and expense cost operating per rate of system production. The evaluation economic analysis of temperature control system for biogas production system was long time payback period because of the hot water system is very expensive. If free the hot water system, Payback period of biogas production system was 0.66 year.

CHAPTER V

CONCLUSIONS

Conclusions

In this study, lab scale anaerobic digestion of food waste operating in thermophilic condition and mesophilic condition. The bioreactor volume is 70 liters and the water contained within the water jacket is 35 liters. The flow rate of water was 15 liters /hour (force circulation) and 1°C temperature difference between the water jacket inlet and outlet. The following conclusions can be drawn from this study:

Determine the biogas tank temperature that suitable for biogas production.

The biogas generation from reactors incubated at mesophilic temperature (20-40°C) and thermophilic temperature (50-65°C). Maximum biogas production occurred at 55°C (38.14 L. of biogas) for a period of 11 days when compared to the other temperatures. Second best was at 50°C (37.44 L. of biogas) for a period of 12 days, followed by 40°C (35.36 L. of biogas) for a period of 15 days respectively

The biogas composition from reactors incubated at 40°C. Maximum methane of the biogas production was 57%. Second carbon dioxide was 35%, followed other gas was 8% respectively.

The biogas composition from reactors incubated at 55°C. Maximum methane of the biogas production was 60%. Second carbon dioxide was 32%, followed other gas was 8% respectively.

The day digestion from reactors incubated at mesophilic temperature (20-40°C) and thermophilic temperature (50-65°C). Minimum day digestion of the biogas production occurred at 55°C (11 days) when compared to the other temperatures. Second best was at 50°C (12 days), followed by 35 and 40°C (15 days) respectively. This lower days digestion, when compared to the other temperatures, is attributed to a temperature of about 55°C is important for bacteria's growth and activity.

Develop the temperature control system for biogas production.

The heating required for the bioreactor was performed using a solar collector combined with biogas energy. Water contained within the jacket of the bioreactor was 35 liters and the bioreactor volume was 70 liters. Heating this volume of water to 35-60°C for the solar collector design.

The solar collector consists of a galvanized steel flat plate of 4.98 m^2 dimensions. The absorber was insulated with a glass wool layer of 4 cm thickness at the bottom. All of these parts were arranged within a box of galvanized steel base and glass top.

The heat exchanger consists of a cylindrical storage tank of 35 L. The storage tank is wrapped with glass wool of 5 cm thickness. Cold water is supplied through the bottom of the flat plate collector and the hot water is retained in the storage tank of the heat exchanger. The outlet water from the bioreactor is fed back to the heat exchanger where it is reheated and then pumped back to the water jacket of the bioreactor.

Heating the bioreactor using solar energy can be approximated by first order dynamics and the night using biogas energy burn hot water. Two types of controllers were an on–off controller, and an analog PID controller. The on–off controller sensor was sensitive to small temperature variations.

Economics analysis temperature controls for biogas production

Economics analysis in this research will be study temperature control system for biogas production cost that the economics analysis consist of evaluation expenses side the other yearly both biogas production system and find out payback period in case.

Payback period of temperature control system for biogas production system was 5.88 year. Consideration total expenses cost per rate of system production and expense cost operating per rate of system production. The evaluation economic analysis of temperature control system for biogas production system was long time payback period because of the hot water system is very expensive. If free the hot water system, payback period of biogas production system was 0.66 year.

Recommendations

Anaerobic digestion is interesting option for treating organic waste. It gives biogas production. However, an experiment on the optimization of continuous process for this experiment was not completely achieved. Therefore, the new concept may be improved the process for further study.

1. The BMP test should be conducted to fresh digestion obtained from the experiments to assess the biodegradability.
2. The AD system should be operated into other system in order to get higher methane yield and to control the process effectively.
3. The hot water system should be used heat waste in order to discount cost.

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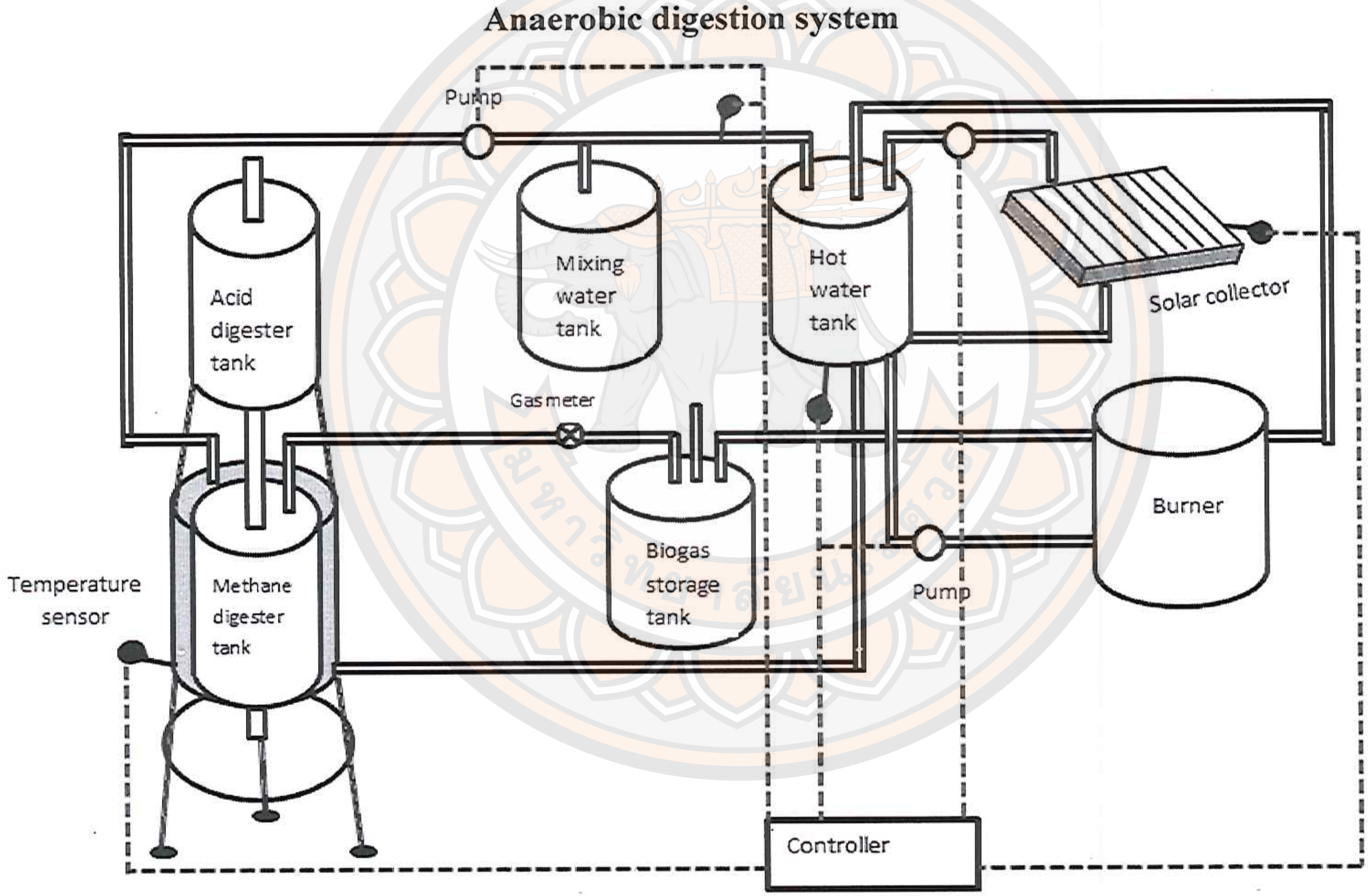
APPENDIX

Appendix A Anaerobic digestion system



Anaerobic digestion system

Appendix B Volume of tank and heat losses rate of hot water

Volume of tank and heat losses rate of hot water

Volume of tank

Size of tank (L)	Diameter (m)	Length (m)
150	0.59	0.77
200	0.59	1.14
300	0.59	1.38
400	0.66	1.39
550	0.82	1.39
750	0.91	1.41
900	1.02	1.42
1,100	1.11	1.44
1,600	1.31	1.45
2,000	1.39	1.78
2,500	1.39	1.91
3,000	1.39	2.25
4,000	1.53	2.73
5,000	1.53	3.19
6,000	1.53	3.67

Heat losses rate of hot water

v1	v2	v2-v1	Flow rate 15 L./h		Flow rate 20 L./h		Flow rate 25 L./h		Flow rate 30 L./h		Flow rate 35 L./h	
			time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)
150	400	250	16.7	1050	12.5	1050	10	1050	8.3	1050	7.1	1050
150	550	400	26.7	1680	20	1680	16	1680	13.3	1680	11.4	1680
150	750	600	40	2520	30	2520	24	2520	20	2520	17.1	2520
200	400	200	13.3	840	10	840	8	840	6.7	840	5.7	840
200	550	350	23.3	1470	17.5	1470	14	1470	11.7	1470	10	1470
200	750	550	36.7	2310	27.5	2310	22	2310	18.3	2310	15.7	2310
250	400	150	10	630	7.5	630	6	630	5	630	4.3	630
250	550	300	20	1260	15	1260	12	1260	10	1260	8.6	1260
250	750	500	33.3	2100	25	2100	20	2100	16.7	2100	14.3	2100
400	550	150	10	630	7.5	630	6	630	5	630	4.3	630
400	750	350	23.3	1470	17.5	1470	14	1470	11.7	1470	10	1470
400	900	500	33.3	2100	25	2100	20	2100	16.7	2100	14.3	2100
550	750	200	13.3	840	10	840	8	840	6.7	840	5.7	840
550	900	350	23.3	1470	17.5	1470	14	1470	11.7	1470	10	1470
550	1100	550	36.7	2310	27.5	2310	22	2310	18.3	2310	15.7	2310
750	900	150	10	630	7.5	630	6	630	5	630	4.3	630
750	1100	350	23.3	1470	17.5	1470	14	1470	11.7	1470	10	1470
750	1600	850	56.7	3570	42.5	3570	34	3570	28.3	3570	24.3	3570
900	1100	200	13.3	840	10	840	8	840	6.7	840	5.7	840
900	1600	700	46.7	2940	35	2940	28	2940	23.3	2940	20	2940
900	2000	1100	73.3	4620	55	4620	44	4620	36.7	4620	31.4	4620

Heat losses rate of hot water (Cont.)

v1	v2	v2-v1	Flow rate 15 L./h		Flow rate 20 L./h		Flow rate 25 L./h		Flow rate 30 L./h		Flow rate 35 L./h	
			time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)	time (h.)	Q (kW)
1100	1600	500	33.3	2100	25	2100	20	2100	16.7	2100	14.3	2100
1100	2000	900	60	3780	45	3780	36	3780	30	3780	25.7	3780
1100	2500	1400	93.3	5880	70	5880	56	5880	46.7	5880	40	5880
1600	2000	400	26.7	1680	20	1680	16	1680	13.3	1680	11.4	1680
1600	2500	900	60	3780	45	3780	36	3780	30	3780	25.7	3780
1600	3000	1400	93.3	5880	70	5880	56	5880	46.7	5880	40	5880
2000	4000	2000	133.3	8400	100	8400	80	8400	66.7	8400	57.1	8400
2000	5000	3000	200	12600	150	12600	120	12600	100	12600	85.7	12600
2000	6000	4000	266.7	16800	200	16800	160	16800	133.3	16800	114.3	16800
2500	4000	1500	100	6300	75	6300	60	6300	50	6300	42.9	6300
2500	5000	2500	166.7	10500	125	10500	100	10500	83.3	10500	71.4	10500
2500	6000	3500	233.3	14700	175	14700	140	14700	116.7	14700	100	14700
3000	4000	1000	66.7	4200	50	4200	40	4200	33.3	4200	28.6	4200
3000	5000	2000	133.3	8400	100	8400	80	8400	66.7	8400	57.1	8400
3000	6000	3000	200	12600	150	12600	120	12600	100	12600	85.7	12600

Appendix C Size of flat plate

Size of flat plate

Flow rate of water (L/h)	Hot water (L/day)	Size of flate plate (m^2)
5	120	1.66
10	240	3.32
15	360	4.98
20	480	6.65
25	600	8.31
30	720	10
35	840	11.63
40	960	13.29
45	1080	14.95

Appendix D Biogas production and composition

Biogas production and composition

Temperature 35 °C

**( ) Data from GC

Days	**Daily biogas production (L)**	**%CH_4**	**%CO_2**	**% Other gases**
Loading 1				
1	2.02	47.90	40.32	11.78
2	1.89	48.92	40.08	11.00
3	2.20	49.54	39.36	11.10
4	2.21	50.65	39.75	9.60
5	2.20	51.73	39.27	9.00
6	2.30	53.95	38.14	7.91
7	2.21	55.47	37.03	7.50
8	2.37	56.73 (55.09)	36.25 (36.99)	7.02 (7.92)
9	2.31	56.49	36.13	7.38
10	2.43	57.85	34.15	8.00
11	2.48	58.79	33.51	7.70
12	2.52	58.64	33.36	8.00
13	2.57	60.91	31.09	8.00
14	2.41	58.73	31.57	9.70
15	2.52	58.83 (58.01)	30.12 (30.89)	11.05 (11.1)

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 2				
1	1.59	47.30	40.30	12.40
2	1.74	49.40	40.00	10.60
3	2.25	50.82	37.43	11.75
4	2.22	52.73	38.02	9.25
5	2.30	52.09	39.71	8.20
6	2.06	53.72	37.11	9.17
7	2.58	54.95 (54.13)	36.56 (37.25)	8.49 (8.62)
8	2.43	56.39	34.42	9.19
9	2.38	57.64	34.10	8.26
10	2.35	57.08	34.35	8.57
11	2.20	58.69	33.57	7.74
12	2.43	59.12	32.34	8.54
13	2.62	59.93	31.65	8.42
14	2.41	60.62 (59.94)	32.12 (31.55)	7.26 (8.51)
15	2.38	58.55	33.68	7.77

Days	**Daily biogas production (L)**	**%CH_4**	**%CO_2**	**% Other gases**
Loading 3				
1	1.66	48.54	40.27	11.19
2	1.94	48.12	41.33	10.55
3	2.04	49.61	39.48	10.91
4	2.54	50.63	40.14	9.23
5	2.46	51.13	40.74	8.13
6	2.49	53.71 (53.02)	38.03 (37.33)	8.26 (9.65)
7	2.32	55.12	37.59	7.29
8	2.45	55.32	36.81	7.87
9	2.36	56.14	34.93	8.93
10	2.43	58.77	32.87	8.36
11	2.55	58.54	32.71	8.75
12	2.53	59.74	31.67	8.59
13	2.51	60.12 (59.64)	31.01 (30.41)	8.87 (9.95)
14	2.65	57.93	34.14	7.93
15	2.42	57.58	33.57	8.85

Temperature 40 °C

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 1				
1	1.92	51.42	39.95	8.63
2	2.34	53.26	37.92	8.82
3	2.19	53.32	39.09	7.59
4	2.31	54.13	36.95	8.92
5	2.67	55.34 (54.86)	35.52 (34.80)	9.14 (10.34)
6	2.50	55.31	35.85	8.84
7	2.11	57.63	35.03	7.34
8	2.33	58.74	32.56	8.70
9	2.41	58.36	33.89	7.75
10	2.02	59.89	31.63	8.48
11	2.13	59.59	30.66	9.75
12	2.47	59.54	33.17	7.29
13	2.68	61.93	30.28	7.79
14	2.74	59.65	32.94	7.41
15	2.54	58.06	35.09	6.85

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 2				
1	1.49	52.49	38.92	8.59
2	1.57	53.17	38.36	8.47
3	1.74	53.20	39.67	7.13
4	2.31	53.19 (52.53)	37.88 (37.16)	8.93 (10.31)
5	2.26	54.26	38.12	7.62
6	2.38	54.31	38.58	7.11
7	2.45	55.54	36.89	7.57
8	2.47	57.91	33.46	8.63
9	2.43	58.55	32.62	8.83
10	2.43	59.13	33.77	7.10
11	2.59	60.47 (59.36)	32.26 (31.52)	7.27 (9.12)
12	2.53	61.31	30.39	8.30
13	2.93	58.39	33.22	8.39
14	2.74	59.36	32.94	7.70
15	2.61	58.75	34.90	6.35
Loading 3				
1	1.47	52.33	39.04	8.63
2	1.84	53.25	38.21	8.54
3	1.9	54.56	37.02	8.42
4	2.07	54.39	38.36	7.25
5	2.38	56.06	35.36	8.58
6	2.42	56.72	33.97	9.31
7	2.32	57.32	34.54	8.14
8	2.53	58.35	33.76	7.89
9	2.58	59.52	32.19	8.29

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
10	2.61	59.34 (58.62)	32.83 (32.13)	7.83 (9.25)
11	2.72	60.61	32.04	7.35
12	2.68	60.17	31.65	8.18
13	2.85	59.35	32.82	7.83
14	2.75	59.62	33.87	6.51
15	2.68	58.51	34.79	6.70

Temperature 45 °C

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 1				
1	0.78	39.31	49.14	11.55
2	1.04	44.19	44.23	11.58
3	1.16	43.90	44.50	11.60
4	1.52	43.13	44.45	12.45
5	1.04	45.38	43.08	11.54
6	1.46	45.43	42.83	11.74
7	1.34	45.87	43.30	10.83
8	1.04	45.93	43.93	10.14
9	1.42	44.46	44.44	11.10
10	1.00	46.25	42.48	11.27
11	1.18	45.85	43.33	10.82
12	1.13	45.62	43.27	11.11
13	1.05	46.54	42.71	10.75
14	1.13	45.35	43.36	11.29
15	1.25	45.82	42.65	11.53

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
16	1.50	46.11 (45.93)	42.76 (42.01)	11.13 (12.06)
17	1.45	48.70	40.82	10.48
18	1.52	45.05	43.65	11.30
19	1.21	47.56	41.59	10.85
20	1.47	47.48	40.90	11.62
21	1.98	49.52	39.71	10.77
22	1.95	50.39	38.78	10.83
23	1.47	50.79 (50.02)	39.03 (38.35)	10.18 (11.63)
24	1.75	48.38	42.54	9.08
25	1.44	48.02	42.23	9.75
Loading 2				
1	0.76	40.36	48.07	11.57
2	1.08	43.74	44.41	11.85
3	1.04	42.49	45.88	11.63
4	1.52	43.19	43.99	12.82
5	1.06	43.17 (42.94)	45.72 (45.01)	11.11 (11.05)
6	1.42	44.26	43.97	11.77
7	1.51	43.06	44.37	12.57
8	1.46	44.74	44.07	11.19
9	1.62	45.54	44.15	10.31
10	1.08	44.42	45.32	10.26
11	1.37	44.46	44.26	11.28
12	1.08	45.19	43.93	10.88
13	1.57	45.91	43.92	10.17
14	1.24	46.55	43.25	10.20

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
15	1.04	45.23	43.61	11.61
16	1.15	45.13	43.55	11.32
17	1.72	48.26	40.24	11.5
18	1.01	46.29	42.32	11.39
19	1.68	48.87 (48.06)	40.50 (39.92)	10.63 (12.02)
20	1.64	50.93	38.64	10.43
21	1.70	49.75	39.87	10.38
22	1.28	50.59	37.59	11.82
23	1.02	49.90	39.76	10.34
24	1.33	47.13	43.58	9.29
25	1.56	46.87	44.90	8.23
Loading 3				
1	0.77	41.21	47.48	11.31
2	1.01	42.01	45.80	12.19
3	1.12	43.60	45.02	11.38
4	1.34	42.83	45.74	11.43
5	1.61	44.27	45.27	10.46
6	1.44	43.46	45.29	11.25
7	1.58	44.90	43.56	11.54
8	1.67	45.41 (44.76)	43.24 (42.48)	11.35 (12.76)
9	1.37	45.26	42.57	12.17
10	1.69	44.72	43.40	11.88
11	1.02	45.21	44.56	10.23
12	1.51	45.24	43.47	11.29
13	1.16	45.78	42.50	11.72

Days	Daily biogas production (L)	$\%CH_4$	$\%CO_2$	% Other gases
14	1.58	45.57	42.99	11.44
15	1.21	46.10	43.61	10.29
16	1.61	46.54	43.14	10.32
17	1.11	47.35	42.08	10.57
18	1.06	46.49	42.35	11.16
19	1.42	47.24	40.98	11.78
20	1.67	49.33	39.61	11.06
21	1.34	50.28	37.97	11.75
22	1.14	50.73	38.66	10.61
23	1.69	49.16	40.81	10.03
24	1.14	49.46	40.99	9.55
25	1.37	47.25	43.78	8.97

Temperature 50 °C

Days	Daily biogas production (L)	$\%CH_4$	$\%CO_2$	% Other gases
Loading 1				
1	2.76	56.57	36.04	7.39
2	2.92	57.45	34.94	7.61
3	2.86	56.39	35.78	7.83
4	2.91	57.71 (57.93)	35.16 (34.48)	7.13 (7.59)
5	2.83	57.77	34.84	7.39
6	2.73	57.56	34.91	7.53
7	3.19	58.92	34.69	6.39
8	3.04	60.19	32.44	7.37
9	3.31	59.63	32.63	7.74
10	3.84	58.49	34.80	6.71

Days	Daily biogas production (L)	%CH$_4$	%CO$_2$	% Other gases
11	3.64	57.38	36.51	6.11
12	3.41	57.41	36.32	6.27
Loading 2				
1	2.23	57.48	35.33	7.19
2	2.16	56.37	35.98	7.65
3	2.39	57.69	34.92	7.39
4	2.52	57.84	34.63	7.53
5	3.04	58.74	33.54	7.72
6	3.58	59.91 (59.17)	33.83 (33.06)	6.26 (7.77)
7	3.31	58.20	34.65	7.15
8	3.46	59.17	34.24	6.59
9	3.66	59.49	33.30	7.21
10	3.29	58.14	34.63	7.23
11	3.83	57.86	35.82	6.32
12	3.64	56.97	36.67	6.36
Loading 3				
1	2.35	56.87	35.59	7.54
2	2.38	57.93	34.21	7.86
3	2.72	56.77	36.15	7.08
4	2.67	57.47	35.38	7.15
5	3.15	58.16	34.56	7.28
6	3.21	58.67	34.97	6.36
7	3.39	58.30	34.95	6.75
8	3.47	59.29	34.12	6.59
9	3.52	58.87	34.61	6.52
10	3.79	57.93	35.96	6.11
11	3.66	57.85	35.8	6.35
12	3.45	56.62	36.96	6.42

Temperature 55 °C

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 1				
1	2.65	59.49	31.06	9.45
2	3.11	59.21	32.24	8.55
3	3.08	58.84	32.51	8.65
4	3.47	60.54	31.40	8.06
5	3.38	59.93	32.44	7.63
6	3.42	59.84	31.37	8.79
7	3.98	60.34	31.91	7.75
8	3.71	61.32	30.32	8.36
9	4.18	61.13	31.20	7.67
10	3.71	60.34	31.92	7.74
11	3.45	59.24	33.49	7.27
Loading 2				
1	2.93	59.28	31.64	9.08
2	3.23	58.83	32.28	8.89
3	3.23	59.82	32.27	7.91
4	3.28	60.59	31.00	8.41
5	3.34	59.92	32.33	7.75
6	3.54	60.77	31.94	7.29
7	3.67	60.48	32.19	7.33
8	3.81	60.36	31.39	8.25
9	4.01	59.99	32.45	7.56
10	3.56	60.95	31.85	7.20
11	3.31	60.28	32.67	7.05

Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 3				
1	2.61	58.56	32.38	9.06
2	3.14	59.62	31.75	8.63
3	3.37	59.89	32.28	7.83
4	3.46	60.29	32.18	7.53
5	3.52	60.30	32.38	7.32
6	3.56	60.57	31.19	8.24
7	3.73	60.32	31.94	7.74
8	3.78	60.21	31.36	8.43
9	3.97	59.94	32.02	8.04
10	3.68	59.43	33.15	7.42
11	3.56	59.51	33.24	7.25

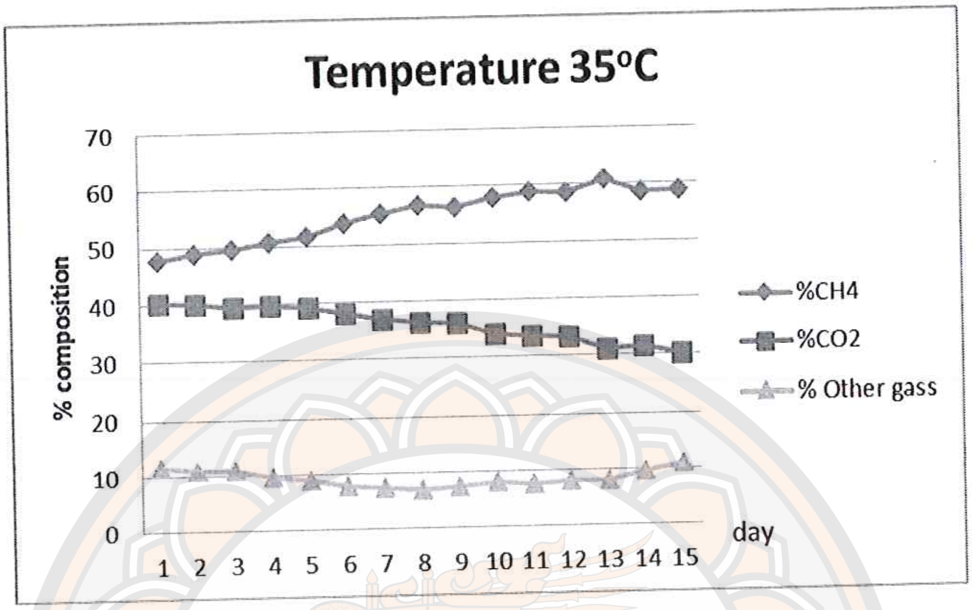
Temperature 60 °C

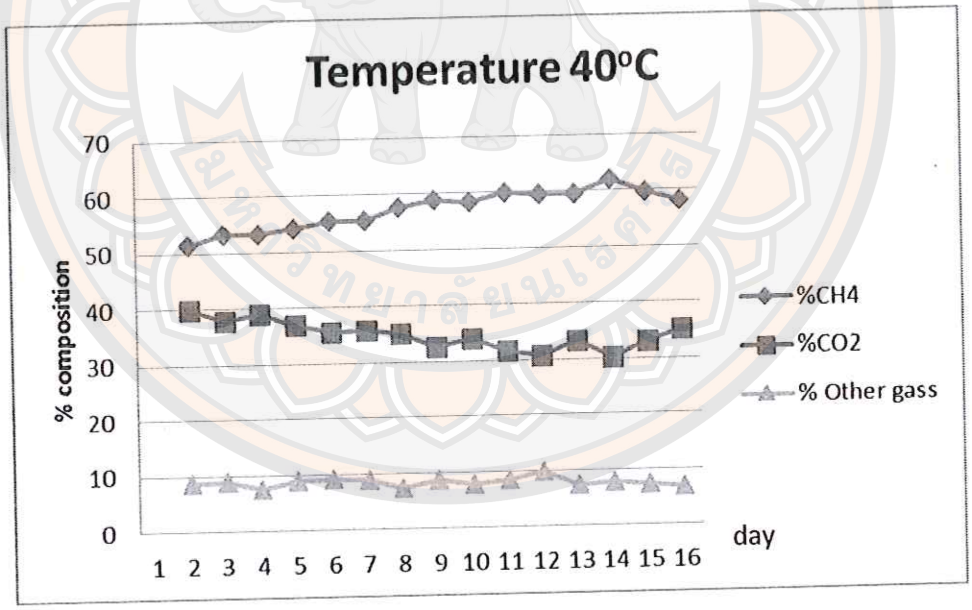
Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
Loading 1				
1	1.14	48.83	37.0	14.14
2	1.37	49.18	37.47	13.35
3	1.68	48.34	38.07	13.59
4	1.17	48.61	38.20	13.19
5	1.22	48.17	38.91	12.92
6	1.27	48.25	39.63	12.12
7	1.49	49.82	38.60	11.58
8	1.89	49.21	39.40	11.39
9	1.72	49.58	39.51	10.91
10	2.05	50.31	39.54	10.15

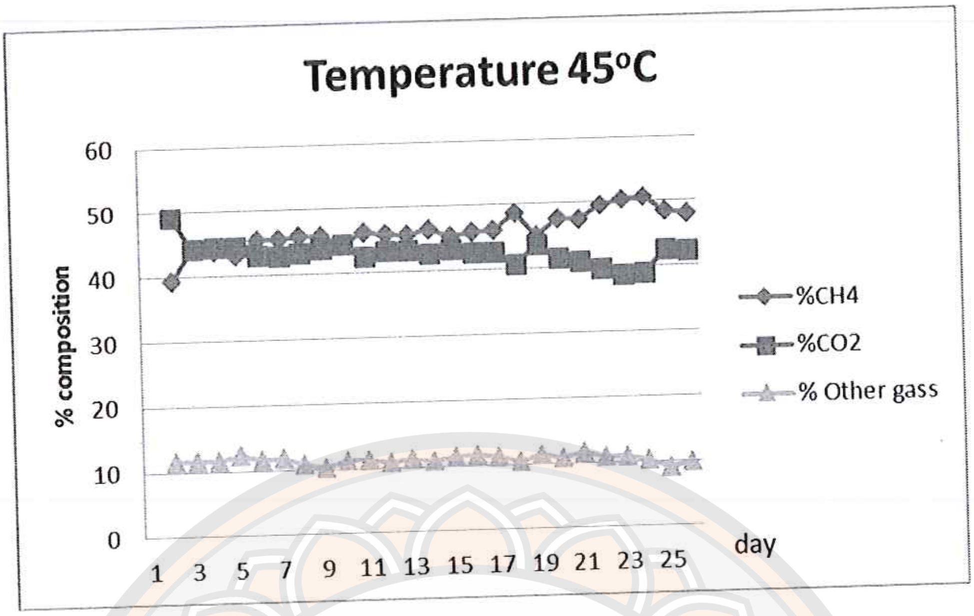
Days	Daily biogas production (L)	%CH_4	%CO_2	% Other gases
11	1.83	50.14	38.98	10.88
12	1.82	49.83	39.34	10.83
13	2.10	50.15	38.47	11.38
14	2.23	50.19	37.95	11.86
15	2.43	52.41	37.28	10.31
16	2.50	52.11	36.78	11.11
17	2.31	50.21	37.92	11.87
18	2.27	49.45	39.06	11.49
19	2.03	48.53	40.77	10.7
Loading 2				
1	1.27	48.14	37.40	14.46
2	1.38	48.45	37.87	13.68
3	1.59	48.73	37.54	13.73
4	1.74	49.40	38.19	12.41
5	1.61	49.83	37.82	12.35
6	1.54	49.93	38.16	11.91
7	1.73	48.76	38.90	12.34
8	1.65	49.37	38.87	11.76
9	1.71	49.72	38.24	12.04
10	1.91	50.52	37.13	12.35
11	1.64	50.61	37.45	11.94
12	1.98	50.75	38.92	10.33
13	2.11	51.59	37.34	11.07
14	2.08	52.06	37.44	10.50
15	2.13	51.63	37.14	11.23
16	2.23	51.57	36.86	11.57
17	2.22	49.91	38.72	11.37
18	2.03	49.17	40.06	10.77
19	1.85	50.64	38.62	10.74

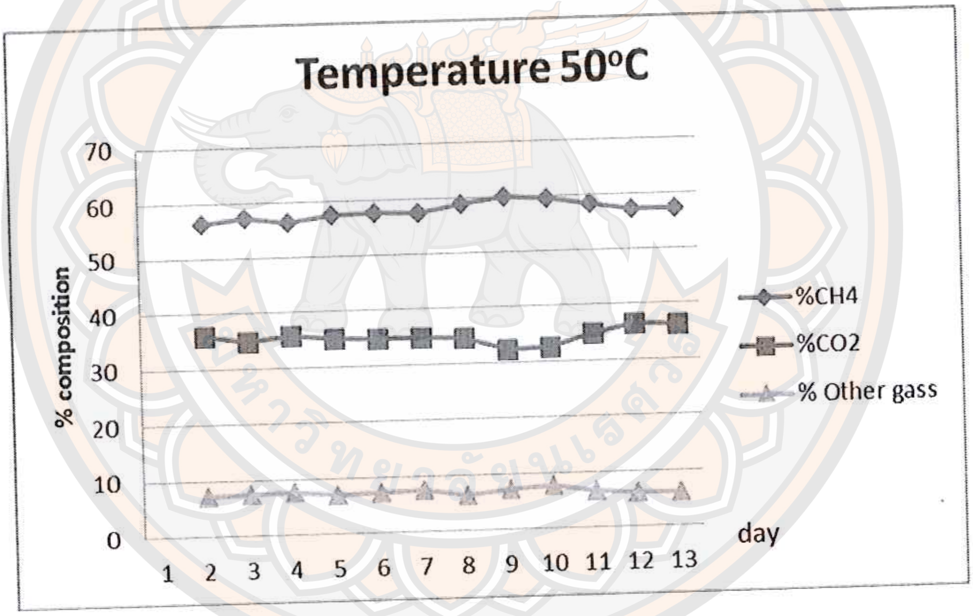
Days	Daily biogas production (L)	$\%CH_4$	$\%CO_2$	% Other gases
Loading 3				
1	1.39	49.34	36.47	14.19
2	1.47	49.62	37.00	13.38
3	1.43	50.50	36.07	13.43
4	1.31	50.28	36.66	13.06
5	1.56	50.86	35.89	13.25
6	1.78	50.12	37.34	12.54
7	1.66	49.72	37.93	12.35
8	1.79	50.85	37.10	12.05
9	1.73	50.14	36.96	12.90
10	1.85	50.02	37.91	12.07
11	2.02	51.31	36.42	12.27
12	1.93	51.11	36.02	12.87
13	2.09	51.09	36.16	12.75
14	2.10	50.92	36.79	12.29
15	2.13	50.56	38.26	11.18
16	2.24	50.73	38.04	11.23
17	2.12	49.99	39.72	11.29
18	2.07	49.82	39.53	10.65
19	1.98	49.31	39.36	11.33

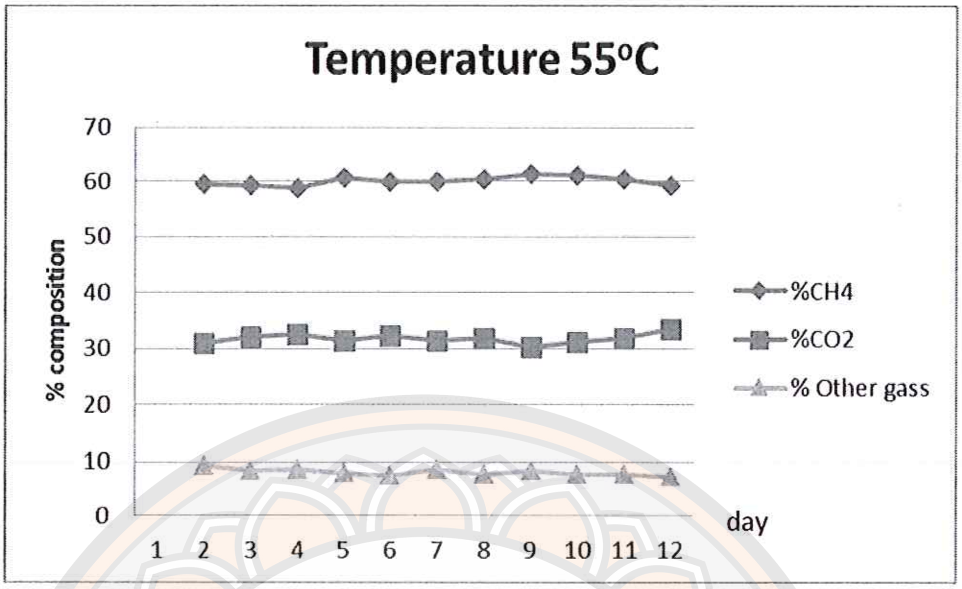
Biogas composition

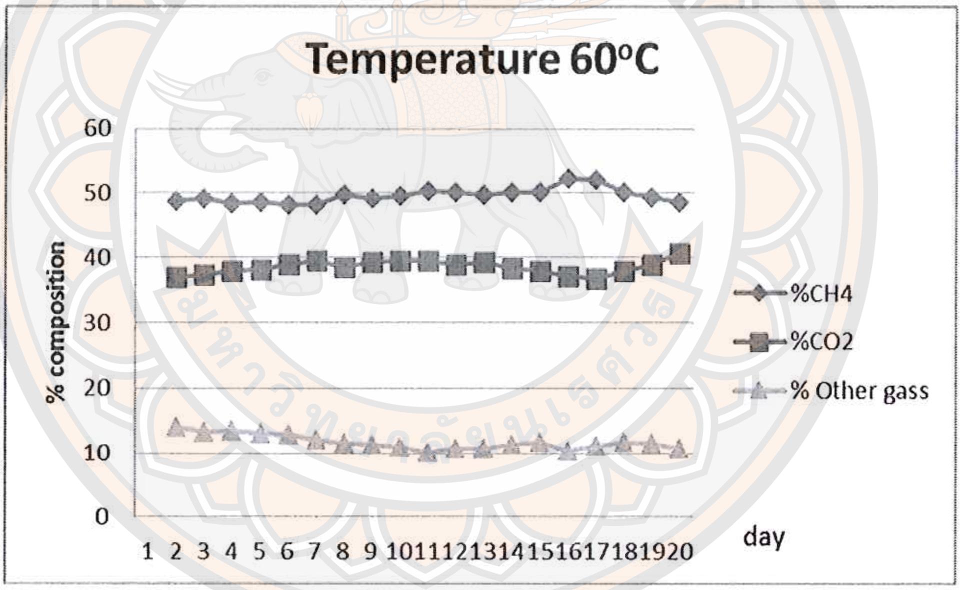





Temperature 45°C
% composition
60
50
40
30
20
10
0
1
3
5
7
9
11
13
15
17
19
21
23
25
day
%CH4
%CO2
% Other gass


Temperature 50°C
% composition
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
day
%CH4
%CO2
% Other gass


Temperature 55°C
% composition
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
day
%CH4
%CO2
% Other gass


Temperature 60°C
% composition
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
day
%CH4
%CO2
% Other gass

Comparison Gas analyzer and GC

Temperature 35 °C

Days	Analysis	%CH_4	%CO_2	% Other gases
Loading 1				
8	Gas analyzer	56.73	36.25	7.02
	GC	55.09	36.99	7.92
15	Gas analyzer	58.83	30.12	11.05
	GC	58.01	30.89	11.1
Loading 2				
7	Gas analyzer	54.95	36.56	8.49
	GC	54.13	37.25	8.62
14	Gas analyzer	60.62	32.12	7.26
	GC	59.94	31.55	8.51
Loading 3				
6	Gas analyzer	53.71	38.03	8.26
	GC	53.02	37.33	9.65
13	Gas analyzer	60.12	31.01	8.87
	GC	59.64	30.41	9.95

Error :			
	CH_4	0.85	%
	CO_2	0.67	%
	Other gases	0.8	%