Chapter from the book *Integrated Waste Management - Volume II*

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Anaerobic Processes for Waste Treatment and Energy Generation

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1. Introduction

As global population increases and developing countries industrialize, energy demand around the world is increasing markedly. World energy consumption is expected to increase by 50% to 180,000 GWh/year by 2020 (Fernando et al., 2006), due primarily to increases in demand from rapidly growing Asian countries such as China and India (Khanal, 2008). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), fossil fuel combustion already contributes 57% of emissions that cause global warming. Thus, to address future energy needs sustainably, renewable sources of energy must be developed as alternatives to fossil fuels.

To aid in developing such renewable energy alternatives, environmental scientists and engineers should consider anaerobic processes for waste treatment as alternatives to aerobic processes. When aerobic processes are used for waste treatment, the low energy compounds carbon dioxide and water are formed; much energy is lost to air – about 20 times as much as with an anaerobic process (Deublein and Steinhauser, 2008). Anaerobic processes produce products of high energy like methane. Methane can be captured and burned as an energy source, and used to power gas-burning appliances or internal combustion engines, or to generate electricity.

Anaerobic processes have been applied for decades in developed countries for wastewater treatment plant sludge stabilization. In recent years, considerable interest has developed in use of anaerobic treatment for a variety of other applications, due to the potential to generate renewable energy. Methane from anaerobic processes is being increasingly utilized as an alternative energy source in developed countries, via large projects that extract methane from landfills or wastewater treatment plants. Smaller plants, on the scale of an individual household or village, can also be a particularly important energy source in rural sectors of developing countries; transportation costs in these locations may limit use of fossil fuels, and lack of cheap and adequate energy hampers rural development. When generated from biomass, especially at a small scale, methane is often called biogas (FAO, 1984; Deublein and Steinhauser, 2008).

In addition to providing a renewable source of energy, anaerobic processes provide some of the simplest and most practical methods for minimizing public health hazards from human and animal wastes – pathogens are destroyed or greatly reduced. Anaerobic processes have been proven for treatment of a variety of organic wastes: solid wastes at landfills, industrial wastewater, human excrement and sludges at wastewater treatment plants, human excrement in rural areas, animal manure, agricultural wastes, and forestry wastes. The

residue is a valuable fertilizer, which is stabilized and almost odorless. This fertilizer is especially a benefit in developing countries, due to its potential to boost crop yields.
This chapter will discuss:

- basics of the anaerobic degradation process,
- methane production: quantities and rates,
- gas production system design, and
- benefits and limitations of anaerobic waste treatment processes.

2. Anaerobic process basics

Anaerobic degradation of organic material (biomass) involves decomposition by bacteria under humid conditions where contact with molecular oxygen is eliminated. The overall process of anaerobic degradation can be represented as (Deublein and Steinhauser, 2008):

$$C_cH_hO_oN_nS_s + y\ H_2O \rightarrow x\ CH_4 + (c\text{-}x)CO_2 + n\ NH_3 + s\ H_2S \qquad (1)$$

where $x = 1/8 * (4c + h - 2o - 3n - 2s)$ and $y = \frac{1}{4} * (4c - h - 2o + 3n + 3s)$.
The above equation can be used to estimate the theoretical methane (CH_4) yield, if the chemical composition of the substrate is known. Primary sludge substrate can be approximated as $C_{10}H_{19}O_3N$, and waste activated sludge (biomass) can be approximated as $C_5H_7O_2N$. The overall process in Eq. 1 can be broken down into stages:

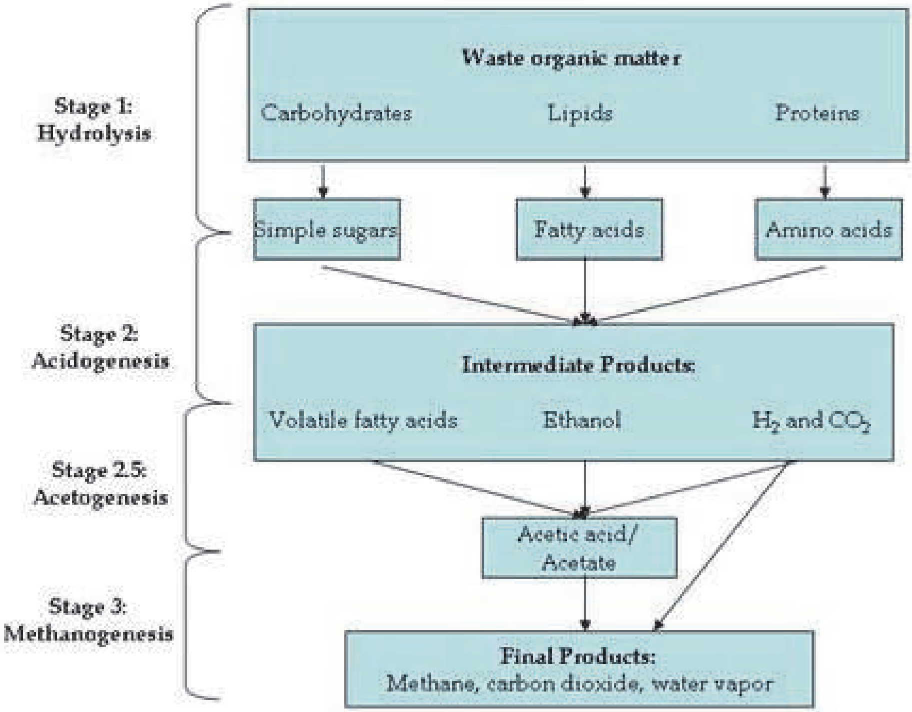

Fig. 1. Anaerobic digestion of organic matter (adapted from Khanal, 2008)

- Stage 1: Polymer Breakdown (Hydrolysis) – carbohydrates, lipids, and proteins are broken down into soluble monomers;
- Stage 2: Acid Production (Acidogenesis) – soluble monomers are converted to volatile fatty acids (lactic, propionic, and butyric acids);
- Stage 2.5: Acetic Acid Production (Acetogenesis) - Volatile fatty acids are converted to acetic acid;
- Stage 3: Methane Production (Methanogenesis) – Acetic acid is converted to methane; carbon dioxide and hydrogen are also converted to methane.

Figure 1 shows a schematic of the overall process of anaerobic digestion of organic matter. The stages are now discussed in more detail.

2.1 Stage 1: Polymer breakdown (hydrolysis)

The primary components of waste organic matter are carbohydrates, lipids, and proteins, as shown in Figure 1. In Stage 1, these components are broken down by cellulolytic, lipolytic, and proteolytic bacteria, respectively, into soluble monomers via hydrolysis (NAS, 1977). In hydrolysis, covalent bonds are split in a chemical reaction with water, as shown in Fig. 2 below.

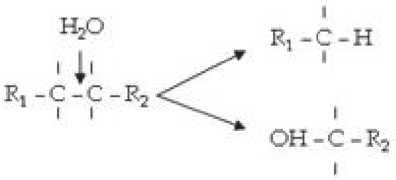

Fig. 2. Hydrolysis (adapted from Deublein and Steinhauser, 2008)

Bacteria of genera *Bacteroides, Lactobacillus, Propioni-bacterium, Sphingomonas, Sporobacterium, Megasphaera, Bifidobacterium* are most common in hydrolysis, including both facultative and obligatory anaerobes. More details concerning bacteria involved in hydrolysis, as well as the subsequent stages of anaerobic digestion, are given by Deublein and Steinhauser (2008).

The rate of hydrolysis is typically described using first-order kinetics according to (Sharma, 2008):

$$r_h = dC_x/dt = -k_h * C_x \qquad (2)$$

where

r_h = rate of hydrolysis, mass/(unit volume * time)

C_x = concentration of hydrolysable substrate x in the reactor, mass/volume

k_h = hydrolysis rate constant, time^{-1}

k_h depends on the specific substrate and temperature. This stage can be rate-limiting for difficult-to-degrade wastes (containing lipids and/or a significant amount of particulate matter, such as sewage sludge, animal manure, and food waste) (Henze and Harremos, 1983; van Haandel and Lettinga, 1994).

2.2 Stage 2: Acid production (acidogenesis)

In Stage 2, acid-forming bacteria (acidogens) convert the products of Stage 1, the soluble monomers, into short-chain organic acids (volatile fatty acids with C>2, such as lactic, propionic, and butyric acids) (Khanal, 2008). Alcohols such as ethanol, hydrogen (H_2), and carbon dioxide (CO_2) are also produced.

The acid formers include both facultative and obligate anaerobic fermentative bacteria, including Clostridium spp., Peptococcus anaerobus, Bifidobacterium spp., Desulphovibrio spp., Corynebacterium spp., Lactobacillus, Actinomyces, Staphylococcus, and Esherichia coli (Metcalf & Eddy, 2004). Deublein and Steinhauser (2008) provide examples of degradation pathways.

The rate of growth of the acidogens can be described according to (Metcalf & Eddy, 2004; Sharma, 2008):

$$r_g = \mu X \tag{3}$$

where

r_g = rate of bacterial growth, mass/(unit volume * time)

μ = specific growth rate, time^{-1}

X = concentration of microorganisms, mass/unit volume

The microbial specific growth rate μ can be described via Monod kinetics (Metcalf & Eddy, 2004; Sharma, 2008):

$$\mu = \mu_{max} * S/(K_S + S) \tag{4}$$

where

μ = specific growth rate, time^{-1}

μ_{max} = maximum specific growth rate, time^{-1}

S = concentration of growth-limiting substrate in solution, mass/unit volume

K_S = substrate affinity constant, or half velocity constant, which represents the substrate concentration at which the growth rate becomes one half of the maximum growth rate, mass/unit volume

Substituting Eq. 4 into Eq. 3 gives:

$$r_g = \mu_{max} * X * S/(K_S + S) \tag{5}$$

The relationship between the rate of soluble monomer (substrate) utilization and rate of growth of the acidogens is given by (Metcalf & Eddy, 2004; Sharma, 2008):

$$r_g = -Yr_{su} \tag{6}$$

where

Y = maximum yield coefficient, mg/mg (defined as the ratio of the mass of cells formed to the mass of substrate consumed)

r_{su} = substrate utilization rate, mass/(unit volume * time)

The substrate utilization rate r_{su} can then be written as:

$$r_{su} = -r_g/Y = -\mu_{max} * X * S/[Y * (K_S + S)] \tag{7}$$

μ_{max}/Y is often replaced by k_m, defined as the maximum rate of substrate utilization per unit mass of microbes. r_{su} is then:

$$r_{su} = -k_m * X * S/(K_S + S) \tag{8}$$

A system of mass balance equations for each substrate and type of microorganism can be solved to obtain substrate and biomass concentrations as functions of time. More detail is provided by Sharma (2008). Monod kinetics can also be used to describe microbe growth and utilization of substrates in Stages 2.5 and 3.

2.3 Stage 2.5: Acetic acid production (acetogenesis)

In Stage 2.5, acetogenic microbes convert the volatile fatty acids and ethanol formed in Stage 2 into acetic acid (CH_3COOH)/acetate (CH_3COO^-), H_2, and CO_2. Examples include (Dolfing, 1988):

$$\text{Propionate} \rightarrow \text{acetate} \quad (\Delta G^\circ = +76.1\ \text{kJ})$$

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad (9)$$

$$\text{Butyrate} \rightarrow \text{acetate} \quad (\Delta G^\circ = +48.1\ \text{kJ})$$

$$CH_3CH_2CH_2COO^- + 2H_2O \rightarrow 2CH_3COO^- + H^+ + 2H_2 \qquad (10)$$

$$\text{Ethanol} \rightarrow \text{acetate} \qquad (\Delta G^\circ = +9.6\ \text{kJ})$$

$$CH_3CH_2OH + H_2O \rightarrow CH_3COO^- + H^+ + 2H_2 \qquad (11)$$

The Gibb's free energy changes for the above reactions are positive, so the reactions are not thermodynamically favorable. However, in a co-culture of H_2-producing acetogenic bacteria and H_2-consuming methanogenic bacteria, a symbiotic relationship exists. Methanogenic bacteria keep the H_2 partial pressure low, which provides a thermodynamically favorable condition for formation of acetic acid/acetate (Khanal, 2008).

Acetic acid is also generated by homoacetogenic microbes, according to (Khanal, 2008):

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O \qquad (12)$$

Other homoacetogenic microbes can convert organic substrates such as formate and methanol into acetic acid/acetate according to (Khanal, 2008):

$$4COOH \rightarrow CH_3COOH + 2CO_2 + 2H_2O \qquad (13)$$

$$4CH_3OH + 2CO_2 \rightarrow 3CH_3COOH + 2CO_2 \qquad (14)$$

The homoacetogenic mesophilic bacteria *Clostridium aceticum* and *Acetobacterium woodii* have been isolated from sewage sludge (Novaes, 1986).

2.4 Stage 3: Methane production (methanogenesis)

Methanogenic bacteria, strictly anaerobic, can use the acetic acid/acetate from Stage 2.5 to form methane, according to:

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (15)$$

The above reaction accounts for up to about 70% of methane produced from anaerobic processes (NAS, 1977; Gujer and Zehnder, 1983). Acetotrophic (also called acetogenic or aceticlastic) methanogens, including bacteria from the genera *Methanosarcina* and

Methanosaeta, perform the conversion (Khanal, 2008). At high substrate concentrations, *Methanosarcina* will dominate. By converting acetic acid to the gaseous products CH_4 and CO_2, Stage 3 reduces the oxygen demand (BOD, COD) of the remaining waste.

Some species, called hydrogenotrophic methanogens, can produce methane from the CO_2 and H_2 formed as products in previous stages, according to:

$$4CO_2 + H_2 \rightarrow CH_4 + 2H_2O \tag{16}$$

The above reaction accounts for up to 30% of methane produced from anaerobic processes (NAS, 1977; Khanal, 2008).

Methanogens can also use formic acid (methanoic acid, HCOOH), methanol (CH_3OH), and methylamines ($(CH_3)_3N$) as substrates, according to (Metcalf and Eddy, 2004):

$$4HCOOH \rightarrow CH_4 + 3CO_2 + 2H_2O \tag{17}$$

$$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O \tag{18}$$

$$4(CH_3)_3N + H_2O \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_3 \tag{19}$$

Besides *Methanosarcina* and *Methanosaeta*, other genera of methanogens include *Methanobacterium, Methanobacillus, Methanococcus*. Methanogens have very low growth rates; their metabolism is usually rate-limiting in anaerobic treatment processes (Metcalf and Eddy, 2004). Long detention times are thus required, which has historically been a drawback of anaerobic processes compared with aerobic ones, although methods of overcoming this drawback have been developed in the last decade (Metcalf and Eddy, 2004). However, since only a small portion of the organic waste is synthesized into new cells, the amount of cells that must be wasted is small, which is an advantage (Metcalf and Eddy, 2004).

Not all of the carbon dioxide produced during Stage 3 (or Stage 2) is released as gas, since it is water soluble. CO_2 in solution reacts with hydroxyl ion (OH^-) to form bicarbonate:

$$CO_2 + OH^- \rightarrow HCO_3^- \tag{20}$$

The bicarbonate concentration depends on alkalinity, temperature, and the presence of other materials in the liquid phase. Conditions favoring bicarbonate production will lower the percent CO_2 in the gas phase, and increase the percent methane. Bicarbonate acts to buffer the solution pH (NAS, 1977).

3. Methane production: Quantities and rates

Factors associated with the waste impact the ultimate quantity of methane that can be produced. Factors associated with the waste, as well as the environment and reactor design, impact how fast methane is produced. This section discusses the impact of waste and environmental factors on methane production. The impact of reactor design will be discussed in the “Gas Production System Design” section. This section also discusses models for estimating methane production, as well as experimentally measured values of methane production.

3.1 Waste factors impacting methane production

Various factors associated with the waste impact both the quantity and rate of methane production:

- Waste composition/degradable organic content
- Particle size
- Organic loading rate (kg/(m^3*d))

The maximum quantity of methane that can be produced depends on waste composition, and in particular the degradable organic content. The theoretical maximum methane yield can be estimated from Eq. 1 above; however, all of the organic content may not actually be able to be degraded by the bacteria. Degradability of the substrate decreases as lignin content increases. The practical amount of methane that can be generated from various wastes is given in Table 2 in Section 3.4.

Waste composition and particle size (along with the environmental factors moisture content, ambient temperature, and pH) have been observed to impact methane production rates. The smaller the waste grain size, the faster methane will be produced, since increased surface area is exposed to bacterial attack. Shredding the waste can increase the rate of methane formation, particularly for wastes with a high content of structural materials (e.g. cellulose, lignin), which make it difficult for microbes to access and degrade the substrate. The yield for substrates like hay and foliage can be increased by up to 20% by shredding (Deublein and Steinhauser, 2008). Shredding should be considered for large lumps of excrement, green cuttings, straw, and other agricultural residuals. Slow-running multiple screw mills, used also in composting technology, are often used.

The methane quantity generated also depends on organic loading rate, as will be discussed in the “Gas Production System Design” section.

3.2 Environmental factors impacting methane production

Environmental factors impacting the rate of methane generation include:

- Temperature
- pH
- Moisture content
- Nutrient content
- Concentration of toxic substances

Each of these factors will be discussed in turn.

3.2.1 Temperature

Anaerobic systems can be designed for temperatures appropriate for mesophilic bacteria (30-40°C) or thermophilic bacteria (50-60°C). Higher temperatures increase microbial activity, with activity roughly doubling for every 10°C increase within the optimal range (Khanal, 2008). Thermophilic systems thus produce methane 25-50% faster, depending on the substrate (Henze and Harremoes, 1983). Below 15°C, almost no methane will be generated (FAO, 1984). The digestion rate temperature dependence can be expressed using the Arrhenius equation (Khanal, 2008):

$$r_t = r_{30}\,(1.11)^{(t-30)} \tag{21}$$

where

t = temperature in °C

r_t, r_{30} are digestion rates at temperature t and 30°C, respectively.

Operating systems in the thermophilic range improves pathogen destruction. However, start-up is slower, and systems are more susceptible to changes in loading variations, substrate, or toxicity (Khanal, 2008).

3.2.2 pH

Acidogens prefer pH 5.5-6.5; methanogens prefer 7.8-8.2. When both cultures coexist, the optimal pH range is 6.8-7.5 (Khanal, 2008). If the pH drops below 6.6, methanogens are significantly inhibited, and pH below 6.2 is toxic (Metcalf and Eddy, 2004). When acid-forming bacteria of Stage 2 and methanogenic bacteria of Stage 3 have reached equilibrium, the pH will naturally stabilize around 7, since organic acids will be removed as they are produced, unless a problem develops. Normally, alkalinity in anaerobic systems ranges from 1000 to 5000 mg/L, which provides sufficient buffering to avoid large drops in pH (Metcalf and Eddy, 2004).

3.2.3 Moisture content

Many landfill studies have confirmed that methane generation rate increases as waste moisture content increases (Barlaz et al., 1990; Chan et al., 2002; Chugh et al., 1998; Faour et al., 2007; Filipkowska and Agopsowicz, 2004; Gawande et al., 2003; Gurijala and Suflita, 1993; Mehta et al., 2002; Tolaymat et al., 2010; Vavilin et al., 2004; Wreford et al., 2000) **.** In many anaerobic systems, the digester is fed a water/waste mixture called slurry, as discussed in “Gas Production System Design”. As long as typical rules of thubfor water addition are followed, moisture content does not limit methane production.

3.2.4 Nutrient content

Methanogens require macronutrients P and N, as well as micronutrients. The amount of P and N required can be calculated by assuming the empirical formula for a bacterial cell to be $C_5H_7O_2N$ (Speece and McCarty, 1964). P and N requirements can also be estimated using COD/N/P ratios, with a minimum ratio of 350:7:1 COD/N/P needed for highly loaded systems (0.8-1.2 kg COD/(kg VSS*day), and a minimum ratio of 1000:7:1 COD/N/P needed for lightly loaded systems (<0.5 kg COD/(kg VSS*day) (Henze and Harremoes, 1983). Phosphoric acid or phosphate salts are commonly used to supply needed additional phosphorous, and urea, aqueous ammonia, or ammonium chloride are used to supply nitrogen (Khanal, 2008).

Trace metals that have been found to enhance methane production include iron, cobalt, molybdenum, selenium, calcium, magnesium, sulfide zinc, copper, manganese, tungsten, and boron in the mg/L level and vitamin B_{12} in μg/L (Speece, 1988).

3.2.5 Toxic substance concentration

High levels of ammonia, soluble sulfides, soluble salts of metals, and alkali and alkaline-earth metal salts in solution (e.g. those of sodium, potassium, calcium, or magnesium) can be toxic to methanogens (NAS, 1977). Maximum allowable concentrations of various substances are given in Table 1 below. In addition, the methanogens are strict anaerobes; thus, their growth is inhibited by even small amounts of oxygen, or highly oxidized material (like nitrates).

3.3 Models for estimating methane production

Anaerobic Digestion Model No. 1 (ADM1), published by the International Water Association, provides a generic model and common platform for dynamic simulations of a variety of anaerobic processes. The model can be used as a tool for research, design, operation and optimization of anaerobic processes. It can be used for a variety of

Constituent	Maximum Recommended Concentration
Ammonia (NH_3)	1500-3000 mg/L
Calcium (Ca)	2500-4500 mg/L
Chromium (Cr)	200 mg/L
Copper (Cu)	100 mg/L
Cyanide (CN^{--})	<25 mg/L
Magnesium (Mg)	1000-1500 mg/L
Nickel (Ni)	200-500 mg/L
Potassium (K)	2500-4500 mg/L
Sodium (Na)	3500-5500 mg/L
Sodium chloride (NaCl)	40,000 ppm
Sulfate (SO_4^{2-})	5000 ppm

Table 1. Maximum recommended concentrations of toxic substances in anaerobic slurries (adapted from OLGPB, 1976)

applications, from domestic (wastewater and sludge) treatment systems to specialized industrial applications. Outputs from the model include gas flow and composition, pH, separate organic acids, and ammonium.

Other specialized models for estimating methane production are available. For example, the U.S. Environmental Protection Agency's (EPA's) LandGEM "Landfill Gas Emission Model" and the IPCC CH_4 generation model are two of the most widely used models for estimating methane generation from landfills.

3.4 Experimental measurements of methane production

Maximum biogas yields for a variety of common materials are given in Table 2. The yields are maximum specific yields of biogas for a given waste, or q_{waste} (maximum biogas produced per total organic solids, volume/mass). Although wood is organic, it is not listed because lignin, the main component of wood, degrades slowly. When values in the table are not given, they could be estimated from similar type wastes. Deublein and Steinhauser (2008) provide biogas yields for additional categories of substrates.

Typically, biogas is 60%-70% methane and 30-40% CO_2 (NAS, 1977; Biogas). The fraction of methane in the biogas increases as the number of C-atoms in the substrate increases (Deublein and Steinhauser, 2008).

For economic reasons, biogas reactors are designed so that 75% of the maximum degradable organic matter is actually decomposed (Deublein and Steinhauser, 2008). This means that the maximum yield values from Table 2 should be multiplied by 0.75 to give an estimate of the practical biogas yield. For large scale plants, laboratory tests using reactors of 4-8 L, and then a **pilot plant** with reactors of size >50L, **should be used to determine the practically attainable methane yield** and rate of gas production. More details are given in Deublein and Steinhauser (2008).

4. Gas production system design

This section focuses on design of larger-scale centralized biogas plants designed for energy generation in developed countries, such as Germany, and smaller-scale units, that may be used in rural areas of developing countries. In either case, the microbiology and design elements are the same. Metcalf and Eddy (2004) and Deublein and Steinhauser (2008) provide a thorough discussion of design of suspended-growth anaerobic digesters for treatment of high-strength industrial organic wastes and sludges from wastewater treatment plants, so these systems will not be discussed in detail here. Design of anaerobic systems specifically at landfills is also discussed elsewhere (e.g. Bagchi, 2004; Rushbrook and Pugh, 1999).

A complete anaerobic system for waste treatment and energy generation includes 3 major components:

- Gas production system
- Gas use system
- Sludge/liquid product use system

This section focuses on design of the gas production system, for which an example schematic is shown in Fig. 3. More information about design of the gas use system can be found in Deublein and Steinhauser (2008) and Khanal (2008). Steps in design of the gas production system include:

1. Determine biogas production requirements,
2. Select waste materials and determine feed rates; size waste storage; determine rate of water addition and size the preparation tank,
3. Design the digester/reactor,
4. Design the gas storage system,
5. Determine system location.

Each of these steps will now be discussed in detail.

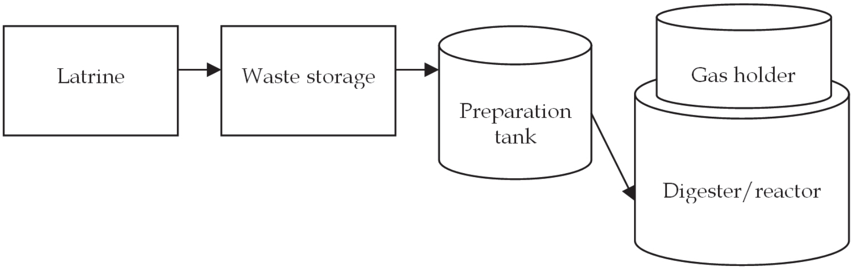

Fig. 3. Schematic of a small-scale biogas production system (adapted from NAS, 1977)

Substrate	**Dry Matter (DM, %)**	**% of Dry Matter that is Organic (oDM)**	**Biogas Yield (m^3/kg oDM)**	**Hydraulic Retention time (days)**	**C/N**
Wastes from households and gastronomy					
Bio waste	40-75	30-70	0.3-1.0	27	
Leftovers (overstored food)	14-18	81-97	0.2-0.5	10-40	
Sewage sludge (households)	5 (night soil)	3.4* (night soil)	0.20-0.75	35-45	2.9-6
Sewage sludge (industry)	--	--	0.30	20	
Flotation sludge	5-24	90-98	0.7-1.2	12	

Animal waste					
General manure from livestock	--	--	0.26-0.28	--	14 (farmyard avg)
Manure from cows	7-20	85-90	0.20-0.50 (per DM)	28-38	18-25
Manure from pigs	5-27.5	90	0.56	22-28	13
Manure from horses	--	--	0.2 – 0.3	--	24-25
Manure from poultry	15-75	75	0.31-0.54	17-22	
Manure from sheep	--	--	0.37-0.61 (per DM)	20	29
Cow dung	--	--	0.33 (per DM)	--	
Slaughterhouse waste	--	--	0.3-0.7	--	2
Animal fat	--	--	1.00	33	
Stomach content of pigs	12-15	80-84	0.3-0.4	62	
Greens, grass, vegetable wastes					
Vegetable wastes	5-20	76-90	0.4	8-20	
Leaves	--	82	0.6	8-20	41
Leaves from trees	--	--	0.210-0.294	--	
Grass cuttings from lawns	37	93	0.7-0.8	10	19
Market wastes	8-20	75-90	0.4-0.6	30	
Straw from cereals	86	89-94	0.2-0.5	--	128 (wheat straw)
Maize straw	86	72	0.4-1.0	--	53
Rice straw	25-50	70-95	0.55-0.62	--	67
Wastes from the food and fodder industry					
Potato pulp, potato peelings	6-18	85-96	0.3-0.9	3-10	25 (potato tops)
Mash from distillations	2-8	65-85	0.42	14	
Wheat flour	88	96	0.7	--	
Oilseed residuals (pressed)	92	97	0.9-1.0	--	
Cereal mash	6-8	83-90	0.9	3-10	
Wastes from other industries					
Egg waste	25	92	0.97-0.98	40-45	173
Waste from paper and carton production	--	--	0.2-0.3	--	
Pulp	13	90	0.65-0.75	--	

* % of total that is organic
Dry matter is equivalent to total solids.

Table 2. Maximum biogas yields and C/N of various substrates (adapted from Deublein and Steinhauser, 2008; OLGPB, 1976; NAS, 1977; Metcalf & Eddy, 2004)

4.1 Determine biogas production requirements

A biogas plant can be designed:

1. to process a given amount of waste material per time, or
2. to produce a given quantity of gas for specific uses.

The second objective is preferable for small-scale units, designed to serve an individual household or small village. In these cases, the biogas unit is the only source of power for the household or village; it is thus important to have sufficient gas available, and the waste can be stored. (NAS, 1977) The first objective could be considered for large-scale units, which are supplementing fossil fuel or other types of power plants for a region.

In the case of design for the second objective, which will be considered here, the engineer must first determine volume of gas needed per day (Q_{gas} = gas production rate, volume/day).

- The biogas may be used directly to power gas-burning appliances (hot water heating, building heating, room lighting, home cooking, refrigeration). In this situation, the engineer must itemize the biogas needed for intended applications and sum up the quantities of gas (see Table 3).
- If the biogas is to be used for electricity production, the thermal efficiency of the turbine must be known. The heating value of biogas is 500-700 Btu/ft^3 (for a gas that is 60%-70% methane and balance CO_2).
- If biogas is to be used to power an internal combustion engine (for water pumping, etc.), the engine efficiency must be known.

Use	**Specification**	**Quantity of Gas Required, m^3/hr**
Cooking	2″ burner	0.33
	4″ burner	0.47
	6″ burner	0.64
	2″-4″ burner	0.23-0.45
	Per person/day	0.34-0.42+
	Per person/day	0.34+
Gas lighting	Per lamp of 100 candle power	0.13
	Per mantle	0.07
	Per mantle	0.07-0.08
	2 mantle lamp	0.14
	3 mantle lamp	0.17
Gasoline or diesel engine	Converted to biogas, per hp (based on 25% efficiency)	0.45-0.51
Refrigerator	Per ft^3 capacity	0.028
	Per ft^3 capacity	0.034
Incubator	Per ft^3 capacity	0.013-0.017
	Per ft^3 capacity	0.014-0.020
Gasoline	1 liter	1.33-1.87
Diesel fuel	1 liter	1.50-2.07
Boiling water	1 liter	0.11

Table 3. Quantities of biogas required for specific applications (NAS, 1977)

Example 1

An anaerobic system is to be designed to provide energy for gas-burning appliances for a village with a population of 150, which live in 28 dwellings. Enough power should be provided for daily cooking, as well as for 2 lamps of 100 candle power per household burning 3 hours per day, and a 2-ft^3 capacity refrigerator for half of the households. Estimate the volume of digester gas that must be produced per day to provide power for the village.

Solution

From Table 3, an average of 0.38 m^3 gas/person/day is needed for cooking. Lamps of 100 candle power require 0.13 m^3 gas/hr, and refrigerators require on average 0.031 m^3 gas/hr/ft^3 capacity. The total biogas required for the village would thus be:
150 persons * 0.38 m^3 gas/person/day
+ 2 lamps/household * 28 households * 0.13 m^3 gas/lamp/hr * 3 hrs/day
+ 1 refrigerator/household * 14 households * 0.031 m^3 gas/hr/ft^3 capacity * 2 ft^3 average capacity/refrigerator * 24 hours/day
= 99.7 m^3 gas/day

4.2 Select waste materials and determine feed rates; size waste storage and preparation facilities

4.2.1 Select waste materials and determine feed rates

The engineer must determine the amount of waste ($\dot{M}_{\text{waste}}$ = waste feed rate, mass/day) needed to produce the biogas estimated in 4.1. The amount of available materials should first be inventoried. Materials to be used as reactor feed should be chosen based on:

- Local availability
- Biogas yield
- Required processing/pre-treatment
- C/N ratio
- Cost

Potential feedstocks for larger-scale biogas plants include municipal sewage water, sewage sludge, industrial wastewater, grass from lawns and other material from landscaping, organic wastes from households, waste from dairies or slaughterhouses, liquid manure, agricultural wastes, organic waste from industry, byproducts from food production. Feedstocks for rural biogas plants include excrement, liquid manure, straw, organic wastes from households, byproducts from agriculture and food production. Although crops can be grown expressly for biogas energy generation, these crops should be chosen carefully to avoid competition with potential food crops.

Quantities of manure provided by various animals are given in Table 4. Maximum biogas yields for a variety of common materials were given in Table 2. The potential biogas generated from various feedstocks can be estimated according to:

$$Q_{\text{waste i}} = q_{\text{waste i}} * \dot{M}_{\text{waste i}} * f_{TS} * f_{oTS} * 0.75 \qquad (22)$$

where
$Q_{\text{waste i}}$ = gas production rate (volume/day) from waste i
$q_{\text{waste i}}$ = maximum specific yield of biogas for waste i (maximum biogas produced per organic total solids, volume/mass)
$\dot{M}_{\text{waste i}}$ = waste feed rate (mass/day) for waste i

f_{TS} = fraction of waste by weight that is solids
f_{oTS} = fraction of total solids by weight that are organic (volatile)
0.75 = factor to account for practical biogas yield
Note that the "Volatile solids" column of Table 4 gives $f_{TS} * f_{oTS}$.

Animal	**Daily manure per 500 kg live animal**		**Volatile solids, % of wet weight**	**Average weight per animal, kg**	**Daily manure per animal, wet weight, kg**
	Volume , m³	**Wet weight, kg**			
Dairy cattle	0.038	38.5	7.98	450-650	34.7-50.1 (42.4 avg)
Beef cattle	0.038	41.7	9.33	485-554	40.4-46.2 (43.3 avg)
Swine	0.028	28.4	7.02	125-270	7.1-15.3 (11.2 avg)
Sheep	0.020	20.0	21.5	41-136 (female); 68-205 (male)	Female: 1.6-5.4 (3.5 avg) Male: 2.7-8.2 (5.5 avg)
Poultry	0.028	31.3	16.8	2-3 (chickens)	0.12 – 0.19 (0.16 avg)
Horses	0.025	28.0	14.3	380-1000	21.3-56 (38.6 avg)

Table 4. Daily manure production for various animals (NAS, 1977)

Required processing/pre-treatment for wastes may include adjusting water content (discussed in 4.2.3), shredding (discussed in 3.1), and/or removal of metals, plastics, glass, and sand. Feed materials should be chosen in combination so that their weighted average C/N ratio (by mass) is around 30, which has been shown through experience to be optimal (NAS, 1977). Since there are few common materials with a suitable C/N ratio, use of more than one source material is typically required (OLGPB, 1978). Although the amount of nitrogen needed is not large, the C/N ratio is important for efficient methane production. If the C/N ratio is too high, nitrogen availability limits the process; on the other hand, if the C/N ratio is too low, ammonia concentrations may become high enough to be toxic to the microorganisms. Supplementing substrates with a high C content with those containing N, and vice versa, can help maintain this ratio. C/N ratios of various wastes were shown in Table 2. The overall C/N ratio can be calculated from:

$$(C/N)_{overall} = \sum_{i=1}^{n} (C/N)_{waste\ i} * f_{waste\ i} \qquad (23)$$

where
$f_{waste\ i}$ = fraction of total waste feed that is waste i, by mass
n = total number of wastes
If $(C/N)_{overall}$ is not close to 30, the combination of waste feedstocks must be adjusted.

Example 2

For the scenario described in Example 1, locally available low-cost feedstocks include household sewage sludge/septage, dairy cow manure (28 cows), poultry manure (56 chickens), and rice straw. Determine waste feed rates for the various feedstocks that will generate the gas estimated in Example 1 with an acceptable overall C/N.

Solution

From Table 2, $q_{\text{waste i}}$, f_{TS}, f_{oTS}, and C/N for the 4 feedstocks are as follows:

Feedstock	**$q_{\text{waste i}}$, m^3/kg oDM**	**f_{TS}**	**f_{oTS}**	**C/N**
household sewage sludge/septage	0.20-0.75 (0.475 avg)	5%	47-83% (65% avg)	2.9-6 (4.5 average)
cow manure	0.2-0.5 (per DM) (0.375 avg)	7-20% (13.5% avg)	85-90% (87.5% avg)	18-25 (21.5 average)
poultry manure	0.31-0.54 (0.425 avg)	15-75% (45% avg)	75%	14 (farmyard avg)
rice straw	0.55-0.62 (0.585 avg)	25-50% (37.5 avg)	70-95% (82.5 avg)	67

We will assume initially that all of the septage, cow manure, and poultry manure are used to generate methane, in order to reduce pathogenic organisms. Rice straw will then be added, in a quantity to provide an overall C/N ratio for the waste mixture of 30.

Average septage (night soil, urine and feces) generation is 1.5 kg/person/day (wet weight) (Metcalf & Eddy, 2004). The mass of septage that would be available per day can thus be estimated as:

$$\dot{M}_{\text{septage}} = 1.5 \text{ kg/person/day} * 150 \text{ persons} = 225 \text{ kg/day}$$

The mass of cow and poultry manure that would be available per day can be estimated from Table 4, last column, as:

$$\dot{M}_{\text{cow manure}} = 42.4 \text{ kg/day} * 28 \text{ cows} = 1187 \text{ kg/day (wet weight)}$$

$$\dot{M}_{\text{poultry manure}} = 0.16 \text{ kg/day} * 56 \text{ chickens} = 9 \text{ kg/day (wet weight)}$$

Gas production for each waste can be calculated according to (22):

$$Q_{\text{waste i}} = q_{\text{waste i}} * \dot{M}_{\text{waste i}} * f_{TS} * f_{oTS} * 0.75$$

$$Q_{\text{septage}} = 0.475 \text{ m}^3 \text{ biogas/kg oDM} * 225 \text{ kg/day} * 0.05 * 0.65 * 0.75 = 2.6 \text{ m}^3 \text{ biogas/day}$$

$$Q_{\text{cow manure}} = 0.375 \text{ m}^3\text{/kg DM} * 1187 \text{ kg/day} * 0.135 * 0.75 = 45.1 \text{ m}^3 \text{ biogas/day}$$

$$Q_{\text{poultry manure}} = 0.425 \text{ m}^3\text{/kg} * 9 \text{ kg/day} * 0.45 * 0.75 * 0.75 = 1.0 \text{ m}^3 \text{ biogas/day}$$

Note that since $q_{\text{waste i}}$ for cow manure was given per DM instead of per oDM, f_{oTS} was not used in calculating $Q_{\text{waste i}}$.

The daily gas production from the septage, cow manure, and poultry manure would be 2.6 + 45.1 + 1.0 = 48.7 m^3/day. Since the C/N for each of these wastes is less than 30, the overall C/N would be less than 30. To raise the overall C/N, a significant amount of rice straw, with C/N of 67, needs to be added. The mass of rice straw to be added can be estimated by first calculating the mass fraction of each waste $f_{\text{waste i}}$ as follows:

$$\dot{M}_{\text{TOT waste}} = \dot{M}_{\text{septage}} + \dot{M}_{\text{cow manure}} + \dot{M}_{\text{poultry manure}} + \dot{M}_{\text{rice straw}} = (225+1187+9)\ \text{kg/day} + \dot{M}_{\text{rice straw}} = 1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}$$

$$f_{\text{rice straw}} = \dot{M}_{\text{rice straw}} / \dot{M}_{\text{TOTAL waste}} = \dot{M}_{\text{rice straw}} / (1421\ \text{kg/day} + \dot{M}_{\text{rice straw}})$$

$$f_{\text{rseptage}} = \dot{M}_{\text{septage}} / (1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}) = 225\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}})$$

$$f_{\text{cow manure}} = \dot{M}_{\text{cow manure}} / (1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}) = 1187\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}})$$

$$f_{\text{polutry manure}} = \dot{M}_{\text{poultry manure}} / (1421\ \text{kg/day} + \dot{M}\ \text{rice}_{\text{straw}}) = \\ =9\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}})$$

Now, Eq. 23 can be solved to yield the mass of rice straw to be added per day, as follows:

$$(C/N)_{\text{overall}} = (C/N)_{\text{rice straw}} * f_{\text{rice straw}} + (C/N)_{\text{septage}} * f_{\text{septage}} + (C/N)_{\text{cow manure}} * f_{\text{cow manure}} + (C/N)_{\text{poultry manure}} * f_{\text{poultry manure}}$$

$$30 = 67 * \dot{M}_{\text{rice straw}} / (1421\ \text{kg/day} + M_{\text{rice straw}}) + 4.5 * 225\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}) + 21.5 * 1187\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}) + 14 * 9\ \text{kg/day}/(1421\ \text{kg/day} + \dot{M}_{\text{rice straw}})$$

$$30 * (1421\ \text{kg/day} + \dot{M}_{\text{rice straw}}) = 67 * \dot{M}_{\text{rice straw}} + 4.5 * 225\ \text{kg/day} + 21.5 * 1187\ \text{kg/day} + 14 * 9\ \text{kg/day}$$

$$42{,}630\ \text{kg/day} + 30\ \dot{M}_{\text{rice straw}} = 67 * \dot{M}_{\text{rice straw}} + 26{,}659\ \text{kg/day}$$

$$37\ \dot{M}_{\text{rice straw}} = 15{,}971\ \text{kg/day}$$

$$\dot{M}_{\text{rice straw}} = 432\ \text{kg/day}$$

If 432 kg/day of rice straw is not available, maize straw or wheat straw, also with high C/N ratios, could be added. The 432 kg/day of rice straw would provide additional methane generation as follows:

$$Q_{\text{rice straw}} = 0.585\ \text{m}^3/\text{kg} * 432\ \text{kg/day} * 0.375 * 0.825 * 0.75 = 58.6\ \text{m}^3\ \text{biogas/day}$$

The total gas production from all 4 wastes would be 48.7 + 58.6 = 107.3 m^3 biogas/day, which is greater than the amount needed to power the village (99.7 m^3 biogas/day), as calculated in Example 1. If the actual gas generated had been less than the amount required, additional feedstocks would need to have been found, or the demand for gas reduced.

4.2.2 Size waste storage

Storage is often required before feedstock wastes are added to the main digester reactor. Plant materials in particular should be left outside to rot for 10 days before being put in the digester (FAO, 1984). Prolonged storage, however, should be avoided if manure is present so that flies do not breed.

The storage shed can be constructed of local materials such as bamboo, tree limbs, and palm thatch, or bricks, tiles, and mortar, depending on available materials. Rain will leach a significant portion of soluble material from manure and excrement, so storage should be covered (NAS, 1977). The volume of storage required can be estimated from:

$$V_s = \sum_{i=1}^{n} \dot{M}_{\text{waste } i} / \rho_{\text{waste } i} * t_i \tag{24}$$

where

V_s = total volume of storage

$\dot{M}_{\text{waste } i}$ = waste feed rate (mass/day) for waste i

$\rho_{\text{waste } i}$ = density of waste i (mass/volume)

t_i = maximum number of days for which storage is desired for waste i

4.2.3 Determine rate of water addition, and size the preparation tank

In many cases, water must be added to the waste to make a slurry. Pure or slightly contaminated water may be added. An overall water content of 75-90%, with 10-25% dry matter, is recommended (Deublein and Steinhauser, 2008). If too little water is added, acetic acid will accumulate, and scum will form on the liquid surface in the digester. The higher the water content, the more CO_2 dissolves in the liquid phase, reducing the CO_2 content of the gas phase, and thus increasing the methane content (Deublein and Steinhauser, 2008). However, if too much water is added, the rate of production per unit volume in the digester will fall.

The volume of water to be added per day (Q_{water}, mass/day) can be estimated given the water content of the fermentation materials, as follows:

$$0.90 = \dot{M}_{\text{water}} / \dot{M}_{\text{TOTAL}} \tag{25}$$

where 0.90 = desired water content (can range from 0.75 to 0.90), and

$$\dot{M}_{\text{water}} = \sum_{i=1}^{n} \dot{M}_{\text{waste } i} (1 - f_{\text{TS waste } i}) + Q_{\text{water}} * \rho_{\text{water}} \tag{26}$$

$$\dot{M}_{TOTAL} = \sum_{i=1}^{n} \dot{M}_{waste\ i} + Q_{water} * \rho_{water} \qquad (27)$$

Solving for Q_{water} gives:

$$Q_{water} = \{9 * \sum_{i=1}^{n} \dot{M}_{waste\ i} - 10 * [\sum_{i=1}^{n} \dot{M}_{waste\ i} (1 - f_{TS\ waste\ i})]\}/\rho_{water} \qquad (28)$$

Water can be added in a preparation tank ahead of the digester. The preparation tank also serves as an equilibrating/mixing chamber, which homogenizes the substrate. The preparation tank is often a vertical concrete cylinder, or a cylindro-conical standing vessel (Deublein and Steinhauser, 2008). The required volume of the preparation tank can be determined from:

$$V_{PT} = \dot{M}_{TOTAL} * t_{PT}/\rho_{water} * 1.25 \qquad (29)$$

where t_{PT} is the desired residence time in the tank and 1.25 is a factor to account for air and fixtures (Deublein and Steinhauser, 2008).

The overall density of the waste slurry is assumed to be approximately equal to that of water, since the water content by weight is 90%. The preparation tank dimensions can then be determined according to the rule of thumb: $H_{PT} = 2 * D_{PT}$, where H_{PT} = height of the preparation tank and D_{PT} = diameter of the preparation tank.

Example 3

Continuing with the information from Examples 1 and 2, estimate the water that must be added to the waste mixture to form a slurry, and size the preparation tank. Assume that the desired t_{PT} is 7 days.

Solution

According to Eq. 28,

$$Q_{water} = \{9 * [\dot{M}_{septage} + \dot{M}_{cow\ manure} + \dot{M}_{poultry\ manure} + \dot{M}_{rice\ straw}] - 10 * [\dot{M}_{septage} (1 - f_{TS\ septage}) +$$

$$\dot{M}_{cow\ manure} (1 - f_{TS\ cow\ manure}) + \dot{M}_{poultry\ manure} (1 - f_{TS\ poultry\ manure}) + \dot{M}_{rice\ straw} (1 - f_{TS\ rice\ straw})]\}/\rho_{water}$$

$$Q_{water} = \{9 * [225+1187+9+432]\text{kg/day} - 10 * [225\ \text{kg/day}\ (1 - 0.05) + 1187\ \text{kg/day}\ (1 - 0.135) + 9\ \text{kg/day}\ (1 - 0.45) +$$

$$432\ \text{kg/day}\ (1 - 0.375)]\}/(1\ \text{g/mL}) * 1000\ \text{g/kg} * 1\text{L}/(1000\ \text{mL})$$

$$Q_{water} = 1522\ \text{L/day}$$

From Eq. 27,

$$\dot{M}_{TOTAL} = \sum_{i=1}^{n} \dot{M}_{waste\ i} + Q_{water} * \rho_{water}$$

$$\dot{M}_{TOTAL} = [225+1187+9+432]\text{kg/day} + 1522\text{ L/day} * 1\text{ g/mL} * 1000\text{ mL/L} * 1\text{ kg/(1000g)}$$

$$\dot{M}_{TOTAL} = 3375\text{ kg/day}$$

According to Eq. 29,

$$V_{PT} = \dot{M}_{TOTAL} * t_{PT}/\rho_{water} * 1.25$$

$$V_{PT} = 3375\text{ kg/day} * 7\text{ days} /(1\text{ kg/L}) * 1.25$$

$$V_{PT} = 29{,}531\text{ L} = 29.5\text{ m}^3$$

Assuming that the preparation tank is cylindrical, $V_{PT} = H_{PT} * \pi * D_{PT}^2/4$. Assume $H_{PT} = 2 * D_{PT}$. Then,

$$V_{PT} = 2 * D_{PT} * \pi * D_{PT}^2/4 = \pi * D_{PT}^3/2$$

Solving for D_{PT} gives: $D_{PT} = [2 * V_{PT} /\pi]^{1/3} = [2 * 29.5\text{ m}^3 /\pi]^{1/3} = 2.66$ m, and $H_{PT} = 5.32$ m

4.3 Design the digester/reactor

Steps in design of the digester/reactor are:

a. Choose flow of wastes through the reactor (batch or continuous) and reactor configuration
b. Choose reactor material
c. Size reactor
d. Choose mixing method
e. Determine heating requirements

Each of these steps will now be discussed in turn.

4.3.1 Choose flow of wastes through the reactor (batch or continuous) and reactor configuration

4.3.1.1 Small systems: Batch systems

Most small systems in rural areas are operated as batch systems. In a batch process, the digester is completely filled all at once. The substrate degrades without anything being added or discharged until the end of the residence time (typically around 3 months) (NAS, 1977). Batch systems can be completely mixed or not mixed. Gas production increases until it reaches a maximum at about half the residence time. At the end of the residence time, most of the residue is emptied into the storage tank, with only small amounts remaining to inoculate the next load (Deublein and Steinhauser, 2008). The system is then cleaned. In a batch system, it is desirable to have 2 digesters so that one can always be in operation (NAS, 1977).

Batch processes have advantages over continuous flow processes in that the reactors are cheaper, and the systems are easier to operate. Since all parts of the substrate have the same residence time, the risk of pathogenic organisms exiting the system is reduced. NAS (1977) discusses other options for flow of materials for anaerobic digesters in rural areas, including semi-continuous plug flow systems and digesters with compartments.

A batch system can have a circular or rectangular cross-section (OLGPB, 1978). OLGPB (1978) gives more details about inlets, outlets, separation walls, and gas outlet pipes for batch systems.

4.3.1.2 Large systems: Continuous flow systems

Most larger systems are operated in continuous flow mode. Continuous flow systems have high volume yields, continuously produce a consistent quality and quantity of biogas, and frequently achieve a higher degree of decomposition.

Hydraulic retention time (HRT, also called hydraulic residence time or hydraulic detention time) indicates the time the slurry containing the waste remains in the reactor in contact with the biomass. HRTs can be shorter for simpler wastes that are easily biodegradable, but must be longer for more complex wastes that are more difficult for microbes to metabolize (Khanal, 2008).

Since anaerobes grow slowly, solids retention time is important in continuous flow systems. Solids retention time (SRT, also called mean cell residence time) controls the microbial mass in the reactor. The SRT must be at least 10-15 days for methanogens, which reproduce slowly. Maintaining a high SRT produces more stable operation and better toxic load resistance (Khanal, 2008).

High SRTs can be achieved by simply using a long HRT and SRT, but this leads to a large reactor. Alternatively, approaches that decouple the HRT from the SRT can be used, via separating and recirculating a portion of the microbes/solids, or immobilizing the biomass. Such approaches allow a high SRT to be maintained, thus preventing washout of slow-growing anaerobes, yet allow reduction in reactor size. 4 approaches for decoupling HRT and SRT are (Khanal, 2008):

1. **Biomass immobilization in attached growth systems** – anaerobes attach to support media (plastic, gravel, sand, or activated carbon) to form biofilms. Examples: *anaerobic filter*, rotating anaerobic contactor; expanded/*fluidized bed reactor*.
2. **Granulation and floc formation** – anaerobic microbes agglomerate to form granules and flocs that will settle well in the bioreactor. Examples: *upflow anaerobic sludge blanket reactor*, static granular bed reactor, *anaerobic sequencing batch reactor*; anaerobic baffled reactor.
3. **Biomass recycling** – Feed with high suspended solids (e.g. wood fiber) enables microbes to attach to solids, forming settlable flocs which are then recycled back to the reactor. Example: *anaerobic contact reactor*/clarigester
4. **Biomass retention** – Membrane integration into reactor retains biomass. Example: *Anaerobic membrane bioreactor*.

For high-solids feed streams, a completely-stirred tank reactor (CSTR) must often be used, which means that HRT=SRT. Pretreatment can reduce the detention time and enhance bioenergy production.

Several types of continuous flow systems are now discussed. Metcalf and Eddy (2004) provides more detailed design considerations for the various reactor types. An additional comparison of common anaerobic reactor designs that decouple HRT and SRT is given in Sattler (2011).

4.3.1.2.1 Anaerobic filter

An example of an attached growth system, anaerobic filters contain a support media on which biomass grow in a biofilm, as shown in Figure 4a. Common support media include synthetic plastic or ceramic tiles, with a high void volume and specific surface area. Since the media retains biomass, a long SRT (on the order of 100 days) can be maintained regardless of HRT. Typically, HRT ranges from 0.5 to 4 days and loading rate ranges from 5 to 15 kg COD/m^3/day. Biomass may need to be wasted periodically to prevent clogging. The configuration can be upflow or downflow (Khanal, 2008).

4.3.1.2.2 Fluidized bed reactor

Another type of attached growth system, a fluidized bed reactor (see Figure 4b) contains microbes attached to biocarriers, such as sand, granular activated carbon, shredded tire, or synthetic plastic media. The biocarriers are expanded by the upflow velocity of feed, which must be 10-25 m/h. Its expansion is 25-300% of its settled volume (Khanal, 2008).

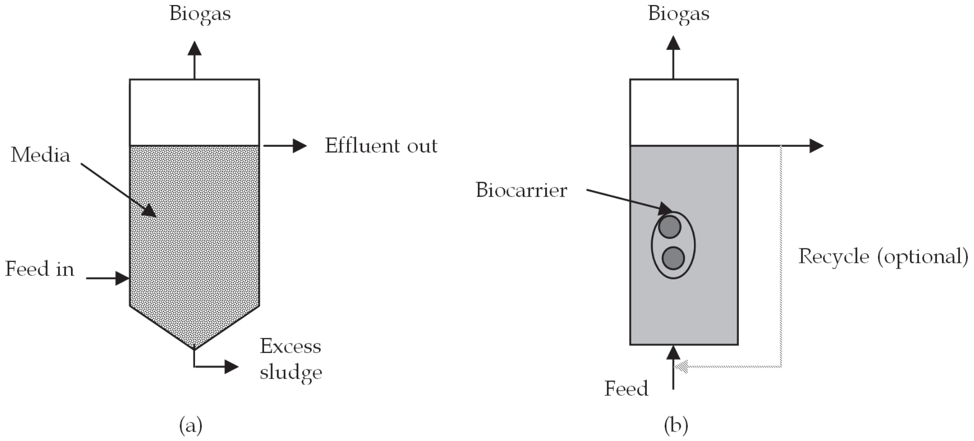

Fig. 4. Schematics of (a) upflow anaerobic filter and (b) fluidized bed reactor (after Khanal, 2008)

4.3.1.2.3 Upflow anaerobic sludge blanket

A type of suspended growth system, an upflow anaerobic sludge blanket reactor (UASB), shown in Figure 5, promotes formation of dense biomass aggregates known as granules, via proper hydraulic and organic loading conditions. Granule diameters range from 1-3 mm, and settle with velocities around 60 m/h. Since the superficial upflow velocity of the waste stream is maintained at <2 m/h, the granules readily settle, forming a sludge blanket at the reactor bottom. Settling of the biomass granules allows decoupling of HRT and SRT. An SRT as long as 200 days can be achieved with HRT as low as 6 hours (Hulshoff Pol et al., 2004). The volumetric organic loading rate (VOLR) can be extremely high: up to 50 kg COD/m^3/day (Khanal, 2008). Khanal (2008) provides more detail about UASB working principles.

4.3.1.2.4 Anaerobic sequential batch reactor

In an anaerobic sequencing or sequential batch reactor (ASBR), all stages of wastewater treatment (filling, reaction, sedimentation, and decanting) happen sequentially in one tank (see Figure 6). Due to sequential operation, a single reactor can serve as a reaction vessel and settling tank, achieving a long SRT regardless of HRT. Biomass is retained due to bioflocculation and biogranulation, similar to a UASB reactor. A larger reactor volume is required than in plants with a continuous process, however, and the process is susceptible to toxic substances. The plants are simpler, though, and are thus often used for industrial wastewater treatment (Deublein and Steinhauser, 2008). The ASBR is highly suited to treatment of animal manure and other biowastes with medium total solids contents (1-4%) (Khanal, 2008).

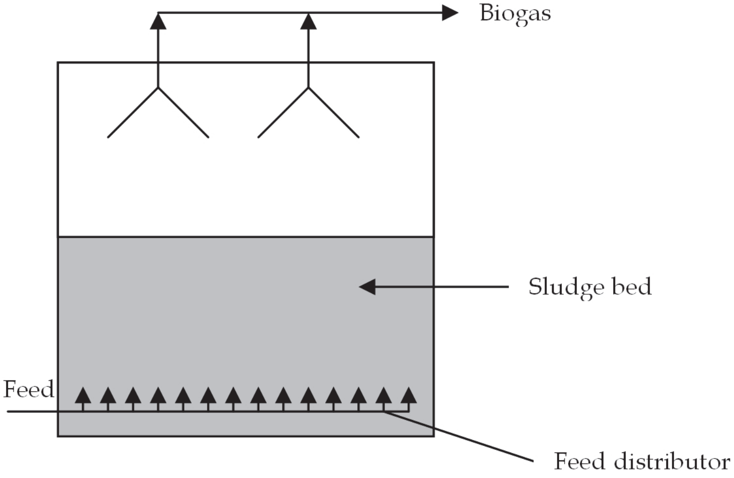

Fig. 5. Upflow anaerobic sludge blanket reactor (adapted from Khanal, 2008)

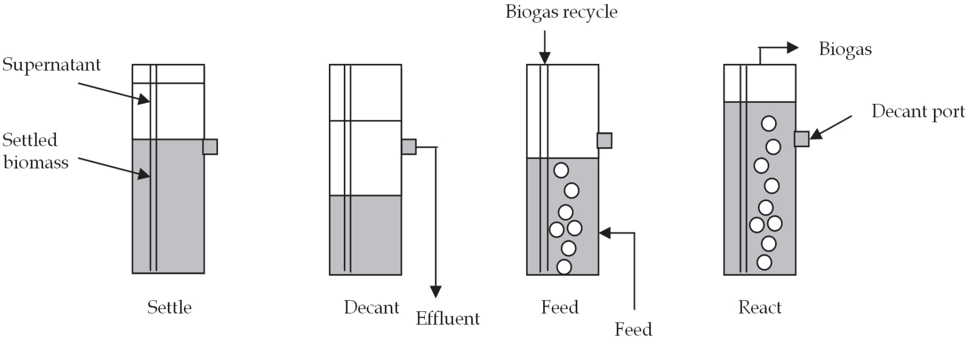

Fig. 6. Anaerobic sequencing batch reactor (adapted from Khanal, 2008)

4.3.1.2.5 Anaerobic contact process

An anaerobic contact process is a CSTR with an external tank to settle biomass, as shown in Figure 7. Settled biomass is recycled back to achieve a long SRT. The degassifier removes

CO_2 and CH_4 bubbles that may attach to biomass and thus prevent settling. The anaerobic contact process is a good choice for feeds with high suspended solids (e.g. wood fiber), which enable microbes to attach to solids and settle. Loading rates range from 0.5 to 10 kg COD/m^3/day (Khanal, 2008).

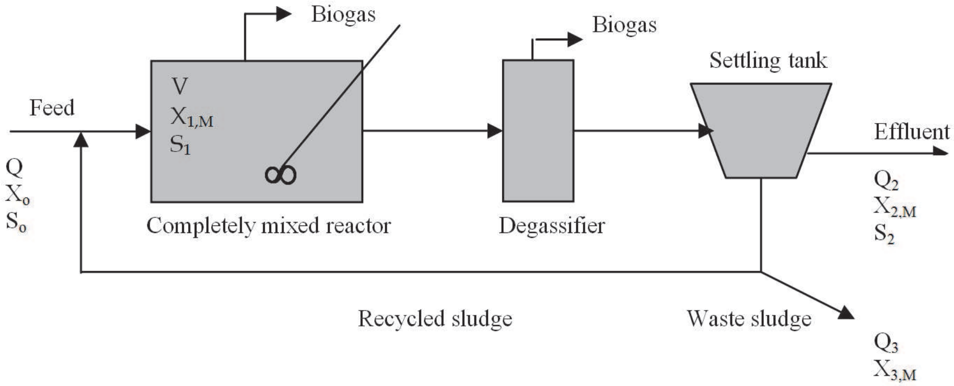

Fig. 7. Anaerobic contact process (after Khanal, 2008)

4.3.1.2.6 Anaerobic membrane bioreactor

An example of a suspended growth system, an anaerobic membrane bioreactor (AnMBR, shown in Figure 8a) uses a membrane, either within the reactor or in an external loop, to aid solids/liquid separation. Since the membrane retains biomass, extremely long SRTs are possible regardless of the HRT (Khanal, 2008).

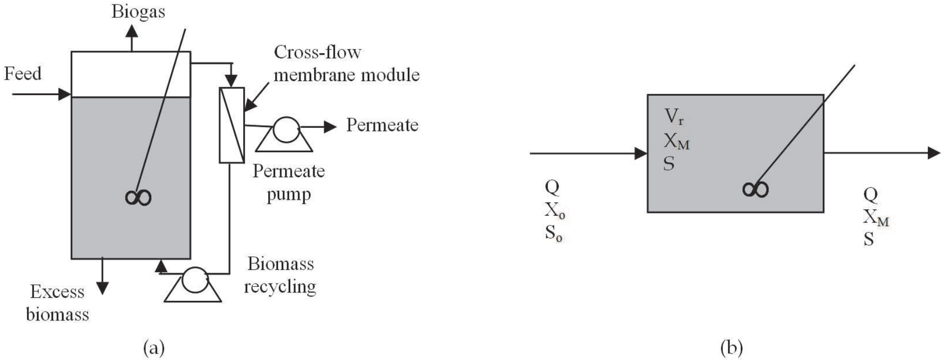

Fig. 8. Schematics of (a) anaerobic membrane bioreactor, with membrane in an external loop, and (b) completely mixed bioreactor (after Khanal, 2008)

4.3.1.2.7 High-rate CSTRs

High-rate anaerobic digesters operated as completely mixed bioreactors, or completely stirred tank reactors (CSTRs), as shown in Figure 8b, have HRT=SRT. They would thus be suitable for high-solids feed streams (TS = 1-6%), including municipal sludge, animal manure, and other biowastes (Khanal, 2008). Required detention time is typically 15 days or less (Metcalf and Eddy, 2004). Mechanical mixing, pumping, and/or gas recirculation can provide mixing.

4.3.2 Choose reactor material

The reactor must be airtight, since the methanogens are obligate anaerobes, and must also prevent liquids from leaking. Considerations in choosing a material for the reactor include:

- Local availability
- Cost
- Ability to maintain heat (thermal insulation capacity)
- Ability to absorb solar radiation (light-colored materials can be painted black to increase solar energy absorption)
- Corrosion-resistant (hydrogen sulfide and organic acids associated with anaerobic degradation can cause corrosion)

Possible materials include:

- Brick and mortar (lime mortar with waterproofing can be substituted for cement where necessary)
- Concrete, sometimes with coating
- Glazed pottery rings cemented together
- Stone
- Glass firer-reinforced plastic
- Fiberglass
- Normal steel with enamel layer or plastic coating for corrosion resistance, stainless steel (high cost may prohibit use in rural areas)
- Thick plastic (for very small tanks only)

Deublein and Steinhauser (2008) provide a more detailed discussion of reactor materials.

4.3.3 Size reactor

The digester size can be estimated using a hydraulic retention time (HRT) or using volumetric organic loading rate (VOLR). Typically, both calculations are performed, and the larger of the two sizes is used, to be conservative.

Typical HRTs for various wastes in anaerobic reactors were given in Table 2. Most of these HRTs are for the mesophilic temperature range. Typical residence times for reactors operated in the mesophilic temperature range are from 20-45 days. Typical residence times for reactors operated in the thermophilic range are around 15 days, since heating increases the rate of microbial activity. From the HRT, the reactor volume V_D can be estimated as (Deublein and Steinhauser, 2008):

$$V_D = Q_{TOTAL} * HRT * 1.25 \tag{30}$$

$$V_D = \dot{M}_{TOTAL} * HRT / \rho_{water} * 1.25 \tag{31}$$

where

Q_{TOTAL} = total waste stream (waste plus water) volumetric flow rate (m^3/day)

1.25 is a factor to account for air and fixtures

M_{TOTAL} = total waste stream (waste plus water) mass flow rate (mass/time)

The volumetric organic loading rate (VOLR) is the mass of dry organic feed/volume of digester/time, or

$$\mathrm{VOLR} = \left(\sum_{i=1}^{n} M_{\text{waste i}} * f_{\text{oTS waste i}} * f_{\text{TS waste i}}\right) / V_D \tag{32}$$

The digester volume can thus be estimated from:

$$V_D = \left(\sum_{i=1}^{n} M_{\text{waste i}} * f_{\text{oTS waste i}} * f_{\text{TS waste i}}\right) / \mathrm{VOLR} \tag{33}$$

This can also be written as:

$$V_D = C_i * Q_{TOTAL} / \mathrm{VOLR} \tag{34}$$

where C_i is the influent waste stream biodegradable COD concentration (mg/L).
The average VOLR for small plants is 1.5 kg oDM/(m^3*d) and for large plants is 5 kg oDM/(m^3*d).
Once the digester volume is found, the dimensions of the digester can then be determined according to the following rule of thumb, assuming a cylindrical digester: $H_D = 0.5 * D_D$, where H_D = height of the digester and D_D = diameter of the digester.

Example 4

Continuing with the information from Examples 1-3, size the reactor.

Solution

First, the digester will be sized based on HRT. From Eq. 31, $V_D = M_{TOTAL} * HRT / \rho_{water} * 1.25$. From Table 2, HRTs for sewage sludge, cow manure, and poultry manure are 35-45, 28-38, and 17-22 days, respectively. (The HRT for rice straw was not given.) Very little of our waste mass is poultry manure. We will choose a 50 day HRT, slightly above the range given for sewage sludge, to be conservative, since a significant portion of the mass of our waste is cow manure.
From Example 3, $\dot{M}_{TOTAL}$ = 3375 kg/day. V_D can then be calculated according to:

$$V_D = 3375\ \text{kg/day} * 50\ \text{days}/(1\ \text{kg/L}) * 1.25 * 1\ \text{m}^3/(1000\ \text{L}) = 211\ \text{m}^3$$

Now, the reactor will be sized based on VOLR. The average VOLR value for small systems, 1.5 kg oDM/(m^3*d), will be used. From Eq. 33,

$$V_D = \left(\sum_{i=1}^{n} M_{\text{waste i}} * f_{\text{oTS waste i}} * f_{\text{TS waste i}}\right) / \mathrm{VOLR}$$

For this example,

$$V_D = [\dot{M}_{\text{septage}} * f_{\text{oTS septage}} * f_{\text{TS septage}} + \dot{M}_{\text{cow manure}} * f_{\text{oTS cow manure}} * f_{\text{TS cow manure}} + \dot{M}_{\text{poultry manure}} * f_{\text{oTS poultry manure}} * f_{\text{TS poultry manure}} + \dot{M}_{\text{rice straw}} * f_{\text{oTS rice straw}} * f_{\text{TS rice straw}}] / \mathrm{VOLR}$$

$$V_D = [225 * 0.05 * 0.65 + 1187 * 0.135 + 9 * 0.45 * 0.75 + 432 * 0.375 * 0.825]\ \text{kg/day} / 1.5\ \text{kgoDM/(m}^3\text{*d)} = 203\ \text{m}^3$$

To be conservative, the V_D value of 211 m^3 based on HRT will be used. Assuming that the digester is cylindrical, $V_D = H_D * \pi * D_D^2/4$. Assume $H_D = 0.5 * D_D$. Then,

$$V_D = 0.5 * D_D * \pi * D_D^2/4 = 0.125 * \pi * D_D^3$$

$$D_D = [V_D / (0.125 * \pi)]^{1/3} = [211 \text{ m}^3 / (0.125 * \pi)]^{1/3} = 8.13 \text{ m}$$

$$H_D = 4.06 \text{ m}.$$

4.3.4 Choose mixing method

In large reactors, mixing is useful in exposing new surfaces to bacterial activity and thus maintaining methane production rates. Incorporating an agitator can considerably reduce the size of the reactor. A rule of thumb is that if the volume exceeds 100 m^3, mixer should be used (OLGPB, 1978). Mixing methods include:

1. Daily feeding of the digester (semicontinuous operation),
2. Installing a mixing device operated manually or mechanically,
3. Creating a flushing action of the slurry through a flush nozzle,
4. Creating mixing action by flushing the slurry tangentially to the digester content,
5. Installing wooden conical means that cut into the straw in the scum layer as the surface of the liquid moves up and down during filling and emptying.

Adequate mixing may be difficult to achieve in an undivided large digester (intended to serve an entire community, for example). Compartments may be particularly useful for large digesters producing >500 ft^3 of gas/day.

4.3.5 Determine heating requirements

Heating speeds the rate of methane production; thus, the detention time can be reduced and the digester size can be smaller than for an unheated unit. However, heating takes energy. The operational cost of providing this energy must be weighed against the reduced capital cost of a smaller digester. For small digesters (producing <500 ft^3 of gas per day), heating using fuel may not be desirable due to maintenance requirements. Solar heating or use of waste heat from an engine-generator may be considered (NAS, 1977). Higher temperatures lower the amount of CO_2 dissolved in the liquid phase, according to Henry's law, and thus increases the percent in the gas phase; this lowers the energy content of the biogas per volume.

The heat requirements for the digester include the amount needed (Metcalf and Eddy, 2004):

1. To raise the incoming slurry to desired digestion temperatures (q_{raise}, or q_R),
2. To compensate for heat losses through the reactor floor, walls, and roof (q_{losses}, or q_L), and
3. To make up losses that might occur in piping between the heating source and tank (q_{piping}, or q_P).

The total heat required is thus:

$$q_{TOT} = q_R + q_L + q_P \tag{35}$$

Heat required to raise the slurry temperature can be calculated from:

$$q_R = \dot{M}_{TOTAL} \, c\Delta T \tag{36}$$

where q_R = heat requirement, Btu/h (W)

M_{TOTAL} = mass flow rate of slurry to be heated

c = slurry heat capacity, which can be assumed to be the same as that of water (1 Btu/lb/°F) (Metcalf and Eddy, 2004)
ΔT = difference between the incoming slurry temperature and the desired reactor temperature.
The maximum heat requirement should be calculated for the coldest month of the year. Heat losses through the reactor floor, walls, and roof can be calculated according to:

$$q_L = \sum_{j=1}^{n} U_j A_j \Delta T_j \tag{37}$$

where q_L = heat loss, Btu/h (W)
U_j = overall coefficient of heat transfer for surface j, Btu/ft²/h/°F (W/m²/°C)
A_j = cross-sectional area of surface j through which heat loss is occurring, ft² (m²)
ΔT_j = temperature drop across surface j, °F (°C)
Overall heat transfer coefficients for typical digester materials are given in Table 5. Expanded plastic slabs of polyurethane can provide insulation for the tank bottom. For the upper portion of the tank, expanded polystyrene slabs, mineral wool mats, plastic foam, leaves, sawdust, or straw can be used to insulate the tank and minimize heating requirements.

Example 5

Continuing with the information from Examples 1-4, estimate the heat that would be required to heat the digester from 40°F to 90°F. Assume that the digester is above ground, and made from 12″ thick concrete walls with insulation. The concrete floor is 12″ thick, in contact with dry earth. The fixed concrete cover is 4″ thick and insulated. Assume no losses between the heating source and tank.

Solution

From Eq. 35, $q_{TOT} = q_R + q_L + q_P$. q_P is assumed to be 0. q_R can be calculated from Eq. 36 according to:

$$q_R = \dot{M}_{TOTAL}\, c\Delta T$$

$$q_R = 3375 \text{ kg/day} * (1 \text{ Btu/lb/°F}) * (90°F - 40°F) * (2.2 \text{ lb/kg})$$

$$q_R = 3.71 * 10^5 \text{ Btu/day}$$

q_L can be calculated from Eq. 37 according to:

$$q_L = \sum_{j=1}^{n} U_j A_j \Delta T_j$$

$$q_L = U_{walls}A_{walls}\Delta T_{walls} + U_{floor}A_{floor}\Delta T_{floor} + U_{cover}A_{cover}\Delta T_{cover}$$

From Table 5, taking the mean value in each range, U_{walls} = 0.125, U_{floor} = 0.06, and U_{cover} = 0.245 Btu/ft²/h/°F.
From Example 4, D_D = 8.13 m and H_D = 4.06 m. The areas of the walls, floor, and cover are thus:

$$A_{walls} = \pi * D_D * H_D = \pi * 8.13 \text{ m} * 4.06 \text{ m} = 103.8 \text{ m}^2 = 1117 \text{ ft}^2$$

$$A_{floor} = A_{cover} = \pi * D_D{}^2/4 = \pi * (8.13 \text{ m})^2/4 = 51.9 \text{ m}^2 = 558.7 \text{ ft}^2$$

$$q_L = 0.125 \text{ Btu/ft}^2\text{/h/°F} * 1117 \text{ ft}^2 (90°\text{F} - 40°\text{F}) + 0.06 \text{ Btu/ft}^2\text{/h/°F} * 558.7 \text{ ft}^2 (90°\text{F} - 40°\text{F}) + 0.245 \text{ Btu/ft}^2\text{/h/°F} * 558.7 \text{ ft}^2 (90°\text{F} - 40°\text{F}) = 15{,}505 \text{ Btu/h} = 646 \text{ Btu/day}$$

$$q_{TOT} = = 3.71 * 10^5 \text{ Btu/day} + 646 \text{ Btu/day} = 3.72 * 10^5 \text{ Btu/day}$$

Item	**Btu/ft²/°F/h**
Plain concrete walls (above ground)	
12″ thick, not insulated	0.83-0.90
12″ thick with air space plus brick facing	0.32-0.42
12″ thick wall with insulation	0.11-0.14
Plain concrete walls (below ground)	
Surrounded by dry earth	0.10-0.12
Surrounded by moist earth	0.19-0.25
Plain concrete floors	
12″ thick, in contact with dry earth	0.05-0.07
12″ thick, in contact with moist earth	0.10-0.12
Floating covers	
With 1.5″ wood deck, built-up roofing, and no insulation	0.32-0.35
With 1″ insulating board installed under roofing	0.16-0.18
Fixed concrete covers	
4″ thick and covered with built-up roofing, not insulated	0.70-0.88
4″ thick and covered, but insulated with 1″ insulating board	0.21-0.28
9″ thick, not insulated	0.53-0.63
Fixed steel cover (1/4 ″ thick)	0.70-0.95

Table 5. Overall heat transfer coefficients for typical digester materials (Metcalf and Eddy, 2004)

4.4 Design the gas storage system

Gas can be stored in a digester with floating cover, or gas from a digester with a fixed cover can be piped into an auxiliary gas holder with a floating cover. Materials for the cover can include mild steel, EDPM rubber, or concrete. The volume of the gas holder depends on the daily gas production and usage. It may be as low as 50% of the total volume of daily gas production, if gas usage is frequent.

Example 6

Continuing with the information from Examples 1-5, determine the volume and dimensions for a cylindrical gas holder to be mounted on top of the digester.

Solution

From Example 2, 107.3 m^3 biogas/day would be produced. Since the gas will be used on a regular basis and withdrawn at a relatively constant rate, the gas holder need have only half the volume of the required daily production. Thus, the gas holder needs to have a capacity of 53.7 m^3. For a cylindrical gas holder to fit onto the top of the digester whose dimensions were determined in Example 5, a suitable diameter would be 7.98m, or 15 cm less than the diameter of the digester. The height of the gas holder would then be:

$$H_H = Vol_H/(\pi \ * D_H^2/4) = 53.7\ m^3/(\pi \ * (7.98m)^2/4) = 1.07\ m$$

4.5 Determine system location

The system location should be:

- At least 50 ft from the nearest drinking water well, to avoid potential contamination (NAS, 1977).
- At least 10 m from any homes, to avoid any methane safety issues (FAO, 1984).
- Out of the sun in hot climates, in the sun in cooler climates (FAO, 1984).
- On firm soil, preferably with a low underground water level (OLGPB, 1978). Away from trees, so roots will not cause cracks (OLGPB, 1978).
- Close enough to place of use to reduce length of connection tubing, and corresponding loss in gas pressure associated with friction with the walls of the tube (OLGPB, 1978).

5. Benefits and limitations of anaerobic processes

Anaerobic treatment processes solve 2 problems at once: waste and energy. Benefits of anaerobic processes compared to aerobic processes are discussed in detail in Sattler (2011), and are summarized briefly here. Benefits of anaerobic systems compared to aerobic systems include:

- Production of usable energy,
- Reduced sludge (biomass) generation/stabilization of sludge,
- Higher volumetric organic loading rate/reduced space requirements,
- Reductions in air pollutants and greenhouse gases,
- Lower capital and operating costs,
- Lower nutrient requirements and potential for selective recovery of heavy metals.

Remaining limitations of anaerobic processes include:

- Requirements for post-treatment,

- Methane loss in the effluent,
- Sensitivity to low temperatures, and
- Attention required during start-up.

6. Summary

Steps in anaerobic degradation of organic material by bacteria include polymer breakdown (hydrolysis), acid production (acidogenesis), acetic acid production (acetogenesis), and methane production (methanogenesis). Various factors associated with the waste impact both the quantity and rate of methane production, including waste composition/degradable organic content, particle size, and organic loading rate (kg/(m^3*d)). Environmental factors impacting the rate of methane generation include temperature, pH, moisture content, nutrient content, and concentration of toxic substances.

Steps in design of a gas production system include:

1. Determine biogas production requirements,
2. Select waste materials and determine feed rates; size waste storage; determine rate of water addition and size the preparation tank,
3. Design the digester/reactor,
4. Design the gas storage system,
5. Determine system location.

Benefits of anaerobic systems compared to aerobic systems include production of usable energy, reduced sludge (biomass) generation/stabilization of sludge, higher volumetric organic loading rate/reduced space requirements, reductions in air pollutants and greenhouse gases, and lower capital and operating costs.

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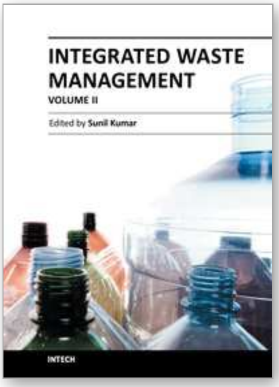

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