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DESIGN AND COST EVALUATION OF ANAEROBIC BIOREACTOR FOR INDUSTRIAL WASTE

MASTER'S THESIS

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Abstract

Industrial wastewater with very high Total Organic Carbon (TOC) is a potential substrate for anaerobic treatment. Continuous Flow Stirred Tank Reactor (CSTR) is the common model of reactor used to treat various kind of wastewater. Development and modification on digester type is still ongoing till this day. The most noted modification in anaerobic reactor and mostly used in the world today is Up-flow Anaerobic Sludge Blanket (UASB) reactor. The main focus of this study is on calculating the design that suitable for treating glycol and organic acid based industrial wastewater. The wastewater is predicted to have total Chemical Oxygen Demand (COD) of 50 kgCOD/m^3 to 100 kgCOD/ m^3 and wide range of salinity. Two models of anaerobic reactor were compared and their parameters calculated based on initial data of the wastewater, Anaerobic Contact reactor and UASB reactor. Influent COD total is assumed to be pre-treated to remove particulate COD, thus COD inlet has nearly 100 % soluble COD. The influent COD is set at 70 kgCOD/m^3 and flow rate of wastewater at 150 m^3/d. Two digester tanks were calculated for Anaerobic Contact reactor, where Acid phase tank has 1526 m^3 volume and Gas phase tank has 5941 m^3. The UASB reactor was split into 4 unit tanks with digester volume at 636 m^3. An external recirculation pump is required to control the up-flow velocity of the UASB. Both of the anaerobic models are predicted to have daily maximum methane production at 4130 m^3/day with energy production rate of 131.3 GJ/day. Costs of the biogas construction were calculated based on its constituent materials. The estimated cost of equipment generation for Anaerobic Contact digester and UASB is 17,237,528.90 Kr and 7,907,535.00 Kr, respectively. The Anaerobic Contact reactor becomes the feasible model for treating the industrial wastewater with high COD concentration based on its ability to withstand shock of wastewater load.

Keywords: *Chemical Oxygen Demand (COD), Continuous Flow Stirred Tank Reactor (CSTR), Anaerobic Contact reactor Up-flow Anaerobic Sludge Blanket (UASB*).

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Stavanger, June 2017

Andri Nursanto

Contents

List of Figures

List of Table

Abbreviations

AMPTS II	Automatic Methane Potential Test System II
CAPEX	Capital Expenditure
COD	Chemical Oxygen Demand
CREST	Cost of Renewable Energy Spreadsheet Tool
CSTR	Continuous Flow Stirred-Tank Reactor
DAF	Dissolved Air Flotation
HRT	Hydraulic Retention Time
IVAR	*Interkommunalt Vann Avløp og Renovasjon*
LCC	Life Cycle Cost
MEG	Mono Ethylene Glycol
MVSS	Mix Liquor Volatile Suspended Solids
NOEC	No Observed Effect Concentration
OLR	Organic loading Rate
SCFA	Short Chain Fatty Acid
SRT	Solids Retention Time
TOC	Total Organic Content
TSS	Total Suspended Solids
UASB	Up-flow Anaerobic Sludge Blanket
VSS	Volatile Suspended Solids

1 Introduction

The world energy consumption is increasing significantly in each year. According to the data from US Energy Information Administration's recently released, it will grow by 48 % between 2012 and 2040 (Figure 1-1). Countries with strong economic growth, including China and India and various countries in Asia, belong to this category[1]. The concerns of sustainable energy sources and the effect of fossil fuel emissions push the countries around the world to find alternative energy source. Renewable energy and nuclear power are the world's fastest-growing energy sources over the projection periods. The consumption of the renewable energy is predicted to be increased by 2.6% per year through 2040[2]. One of the energy source categorized as renewable energy is biogas.

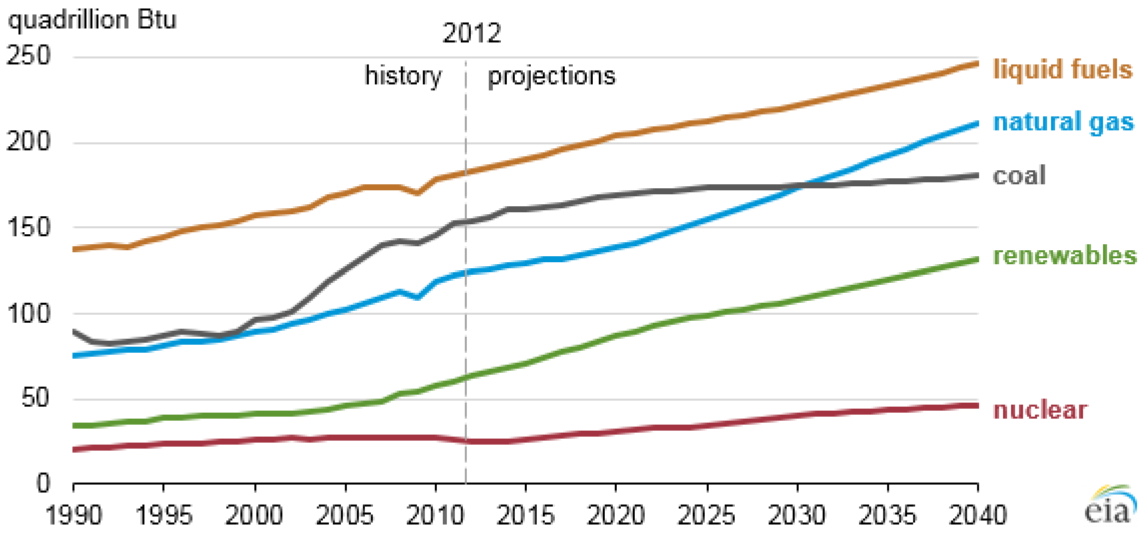

Figure 1-1 Predicted world energy consumption by source, U.S. EIA

Biogas is combustible gas, produced from organic material degradation, where the microbial activity takes place in the process in anaerobic environment and under particular temperature. Biogas consists of around 60% methane gas and 40% carbon dioxide, and small constituent gas in small number. The biogas is produced from fermentation process where organic matter is degraded into smaller particles and produces methane gas as part of the chain reaction. Anaerobic degradation occurres in conditions where no oxygen present in any form, including NO_x. Anaerobic degradation typically occurs in the stomach of animals, sediments, municipal landfills, wastewater line, etc. This process can be utilized for human benefits by controlling the process in wastewater treatment and other facilities. Municipal wastewater and industrial wastewater can be treated anaerobically depending on the substrate contained in it.

Industrial wastewater with total organic carbon (TOC) content has the potential as a substrate for biogas production. Typical TOC content of the feed for biogas production ranges between 10.000-20.000 mg TOC/kg. One of the examples of industrial wastewater, which has bio-potential as biogas substrate, is glycol-based wastewater. This is a chemical commonly used in the industry as coolants and antifreeze in car or vehicle, helping the engine to run during winter and freeze condition.

Anaerobic treatment facilities are commonly installed in the line of wastewater treatment in agricultural and food industry. Planning and construction of biogas production plant in large-scale is preferred compared to small-scale production plants, because the available technology present is expensive, especially the biogas purification system. A high number of anaerobic digester plantations was built worldwide with large digester capacity up to 10.000 m^3. Two types of standard substrate used for this biogas digester are the agriculture waste and industrial wastewater.

1.1 Collaboration with Industry

This study was part of the Master project in cooperation with *Norwegian Technology AS* and Environmental Technology Study Program, University of Stavanger. *Norwegian Technology AS* is a company that provides assistance to handling industrial wastewater and sells technology in the wastewater treatment fields. In this study, calculation modeling of the anaerobic reactor was conducted to acquire design parameter suitable to treat a type of wastewater which contains glycol and organic acid.

Organic wastewater containing glycol with a high concentration of total COD is available in the markets, and the demand to treat the waste is high. Norwegian Technology AS as a company that helps handling wastewater plans to utilize the high COD concentration into biogas in site. The planned project is to build the anaerobic bio-digester in the line of wastewater treatment and connect the line of biogas production with IVAR biogas purification unit in Mekjarvick, Stavanger. The flow process includes the wastewater storage and effluent water line to the nearest sea or fiord.

By the time the author finishes writing the thesis, the Norwegian Technology AS will already have wastewater storage unit and DAF (Dissolved Air Flotation) unit in site. The idea is to connect the units with the anaerobic digester process line. Available location for the treatment was suggested to be close to the Norwegian Technology AS or the space near the pier and jetty, where the wastewater can be transported to this location.

1.2 Objectives

The main objective of this master thesis is to calculate the design parameter and settings for two types of anaerobic digester; Anaerobic Contact Reactor and Up-flow Anaerobic Sludge Blanket (UASB) reactor, which will be installed in the *Norwegian Technology AS* area in Mekjarvick, Stavanger. Furthermore, a simple bio-potential test is to be conducted to get information regarding bio-pesticide contents in industrial glycol-based wastewater. Specific objectives of the thesis are defined in subchapter 2-7.

1.3 Thesis outlook

This master thesis is entitled: "Design and Cost Evaluation of Anaerobic Bio-reactor for Industrial Waste" and it divided into seven chapters. Chapter 1 presents the introduction and background information regarding the study of designing anaerobic reactor. Chapter 2 consist of the literature review to understand in depth the characteristic of the anaerobic degradation and its digester design. Chapter 3 presents the methods and steps used for this case of study. Chapter 4 showed the result from the steps conducted in Chapter 3. Chapter 5 illustrate the analysis of the result showed in Chapter 4. Chapter 6 and Chapter 7 showed the conclusions and suggestions made for the study. Appendixes are included to present supporting materials of the whole study.

2 Literature Review

This Chapter describes the basic concept of the anaerobic process including the stoichiometry for measuring biogas potential, type of conventional digester, parameters affecting the gas production, biological treatment, and pre-treatment for biogas production.

2.1 Biogas

Biogas produced from the anaerobic digestion by a consortium of bacteria, including methanogenic bacteria. Methanogenic bacteria plays a crucial role in the final stage in the process of anaerobic digestion. Under symbiotic effects of various anaerobic bacteria, molecular organic matters are decomposed into methane and carbon dioxide [3]. Methane produced from bio-digestion can be used as an energy source and converted into another form of energy, such as heat, electricity, or it can also be used directly for cooking because of its inflammability.

Historically, biogas was discovered by Alessandro Volta, who started collecting the gas produced from the sludge. He found that the formation of gas shows the process of fermentation and gas produced in contact with air will explode. At that time, the structure of methane was still unknown until Avogadro in 1821 successfully identified methane structure. The biogas generation in anaerobic conditions was firstly stated by Popoff in 1875. In 1876, Herter reported that based on the stoichiometry, methane and carbon dioxide can be formed from acetate found in the wastewater sewage[4]. After that, Louis Pasteur in 1984 was trying to produce biogas from manure collected from the streets in Paris. Together with his student Gavon, he planned to produce 100L of methane from $1m^3$ dirt under fermentation at a temperature of 35°C. Pasteur claimed that the rate of biogas production could be sufficient to illuminate streets of Paris[5]. From here on the application of renewable energy begins. Until now, the technology of biogas utilization is still in developing state and currently used as an alternative energy source around the world. Biogas technology is feasible to implement around the world. However, the cost of biogas production is increasing inversely proportional to the sinking temperature [5]. The cost is related to the heating system, size and capacity of the reactor, coating and insulation.

Biogas contains 60-70% methane and 30-40% carbon dioxide. It also contains other gases such as hydrogen, hydrogen sulfide (H_2S) and a variety of gases with low percentages around 1-5%. The primary objective of biogas production is to utilize the higher content of methane gas conversion from the substrates. Some methods are used to increase the effectiveness of the gas production such as pre-treatment of the wastewater sludge before entering the digester. A gas scavenger is required to purify the biogas and remove or reduce the unwanted components.

2.2 Anaerobic Digestion

The biological gasification process is referred to anaerobic digestive. The process represents the microbial conversion of organic matter into methane and other gases in the absence of oxygen[6]. The process can take place at temperatures ranging from 10°C to more than 100oC. Anaerobic digestion can ferment bio-degradable material in the absence of oxygen to produce methane and carbon dioxide.

Three stages are included in the anaerobic degradation pathway [7]:

1 Hydrolysis: Stage in which the polymer chains are broken down into simple monomers.

2. Acetogenesis: Volatile fatty acids converted into the acetic acid form, carbon dioxide, and oxygen.

3. Methanogenesis: Acetate is converted into methane and carbon dioxide, while hydrogen consumed.

Figure 2-1 shows the pathway of molecular degradation under anaerobic digestion. In the absence of inorganic electron acceptors other than H_2 and CO_2, the stages are; Hydrolysis, fermentation, β-oxidation, acetogenesis, acetate oxidation, methanogenesis. There are two pathways to produce methane from methanogenesis stage; organic waste can be broken down into hydrogen and carbon dioxide or converted to a simpler methyl compounds.

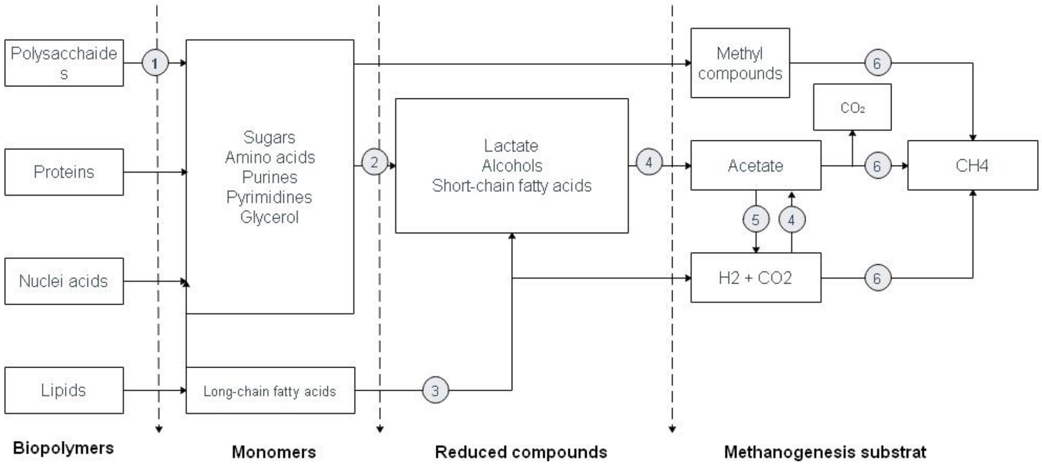

Figure 2-1 Pathway of molecular degradation[8]. Hydrolysis (1), fermentation (2), β-oxidation (3), acetogenesis (4), acetate oxidation (5), methanogenesis (6)

2.2.1 Hydrolysis

At hydrolysis stage, the organic material is converted to soluble compounds, then it is to be hydrolyzed into monomers. The monomers produced by hydrolysis reaction undergo fermentation process [9]. Water and other molecules are transformed into the functional groups that will provide two end products, one of which will contain hydrogen as cation and the other will contain hydroxyl as an anion. The process of hydrolysis is a reaction that is used to break polymers into simpler molecules. Insoluble organic polymers, such as carbohydrates, cellulose, proteins, and fatties, are broken down by hydrolytic bacteria. For example, the fat is broken down into fatty acids; proteins are converted into amino acids; polysaccharides are converted into monosaccharides and nucleic acids form purine and pyrimidine [10]. Hydrolysis of particulates are modelled as a first order reaction with respect to hydrolysable compounds (see Equation 2-1):

$$r_{hydr} = k_h \cdot X_S$$

Equation 2-1

k_h= 0.3 – 0.7 d^{-1}

2.2.2 Fermentation

The fermentation process is rapid and the growth rate of the microorganisms follow Monod equation model. The microorganisms convert monomers into SCFA (short chain fatty acids), alcohols and hydrogen. The reactions are presented below (see Equation 2-2 to Equation 2-4):

$Acetic\ acid$: *Equation 2-2*

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

$Propionic\ acid$: *Equation 2-3*

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$$

$Butiric\ acid$: *Equation 2-4*

$$CC_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2CO_2 + 2H_2$$

2.2.3 Acetogenesis

At this stage amino acids, sugars, and fatty acids degrade into intermediated products, such as lactate, succinate, butanol and ethanol by fermentative bacteria called acetogenic bacteria[10]. Anaerobic conversion of fatty acids and alcohols is running to form acetic acid by consuming hydrogen and carbon dioxide. The formed of acetic acid is to be used to produce methane at a later stage. The reactions in acetogenesis step presented below (see Equation 2-5 to Equation 2-7):

$Propionic\ acid$: *Equation 2-5*

$$CH_3CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + CO_2 + 3H_2$$

$Propionic\ acid$: *Equation 2-6*

$$C_2H_5OH + H_2O \rightarrow 2CH_3COOH + 2H_2$$

$Butiric\ acid$: *Equation 2-7*

$$CH_3CH_2CH_2COOH \rightarrow 2CH_3COOH + 2H_2$$

The growth rate of acetogenic organisms is slightly higher than methanogenic organisms but still lower than fermentation. The μ_m (maximum specific growth rate) of the microorganisms are ~ 0.5 – 0.8 d^{-1}.

2.2.4 Methanogenesis

In the final stage, which called methanogenesis, acetate is converted to methane and carbon dioxide. Hydrogen is used as the electron donor and carbon dioxide as an electron acceptor to produce methane[11]. There are two groups of microorganisms responsible in this step: an organisms that use acetic acid as substrate and the organisms that utilize hydrogen and carbon dioxide to generate methane. The reactions involved in this step shown below (see Equation 2-8 and Equation 2-9):

$$2CH_3COOH \rightarrow CO_2 + 4H_2$$ *Equation 2-8*

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$ *Equation 2-9*

The growth rate of methanogenic organisms is low, μ_m are recorded at range ~ 0.3 – 0.5 d^{-1}. When the wastewater's COD of influent contain almost soluble COD, hydrolysis became less significant and methanogenesis became rate limiting reactions[12].

Methanogenic bacteria is naturally found in swamp water and intestine of ruminant animals, where anaerobic conditions present. These microorganisms are very sensitive to the environment that is why the bio-reactor should operate at the right temperature, pH and other process parameters.

2.3 Process Parameters

Crucial parameters of the biological processes need to be monitored to preserve the bacteria in good condition. The influence of these parameters is presented below.

2.3.1 Temperature

There are two types of Methanogenic bacteria, which are classified by its optimal temperature: *mesophilic* bacteria and *thermophilic* bacteria. Mesophilic bacteria is active at temperatures around 32-42 °C or ambient temperature at 20-45 °C. The thermophilic bacteria, on the other hand, is active at temperatures around 48-55 °C and at high temperatures up to 70 °C.

Methanogenic bacteria that used in biogas industry is mesophilic bacteria, and only a few systems are using thermophilic bacteria. Methanogenic bacteria are sensitive to temperature changes. However, thermophilic are more susceptible to temperature changes than mesophilic bacteria. The effect of changing temperature decreases activity of bacteria. The bacterial activity is maintained with little change in temperature (stable temperature) over a range of ± 20 °C[7].

2.3.2 pH

The methanogenic microorganisms can live in conditions with neutral pH (~ pH 7) or slightly alkaline conditions. The optimal pH to form methane is 6.7-8.2. However, the species of bacteria like *methanosarcina.sp* are able to survive at pH <6.5. Acidity in the digester needs to be monitored to ensure that bacteria is always in optimum conditions. The concentration of volatile fatty acids is an important parameter to control whether the process went well or not.

2.3.3 Type of Substrate

The substrate is food for bacteria. Substrate is composed of large molecules that can be broken down into smaller molecules by bacteria. The specific kind of substrate is necessary for determining the rate of anaerobic digestion. For example, the time for hydrolysis and acidification from sugar is shorter than from cellulose.

2.3.4 Nutrients Ratio (C / N)

Microorganisms need carbon and nitrogen in the process of assimilation [7]. Deublin stated that proper conditions are the ratio of C: N: P: S is 500-1000: 15-20: 5: 3 respectively, and the ratio of COD: N: P is 800: 5: 1. Nutrients ratio is imperative because if the C/N ratio is too small, it will increase the production of ammonia and will inhibit the production of methane. And if the C/N ratio is too high, the nitrogen deficiency can affect the possibility of the formation of energy derived from protein.

2.3.5 Loading Rate

Level of substrate loading or loading rate plays a significant role in determining the amount of substrate that will be fed into digester every day. If there is a shortage of substrate, the resulting production is not maximum but if there is excess of substrate volume, an effect of accumulating of fatty acids will inhibit the production of methane. Therefore, the exact loading rate is vital for this process.

2.3.6 Retention Time

Retention time is the time substrate is kept in the reactor under digestion process. In the continuous system, retention time is determined by dividing the volume of the digester with a given amount of substrate daily (organic loading rate). The batch system retention time is the time during the experiment because there is no movement of the batch system turnover reactants, so worth staying. For example, for 10 L of digesters with 500 mL of Organic Loading Rate (OLR), Hydraulic Retention Time (HRT) is 20 day. Thus the substrates will be kept in the reactor during 20 days.

2.3.7 Recycled Solids and Wasted Solids

By definition, the recycled solids are the sludge that carried out to the effluent of the digester and then recycled back into the inlet stream of the digester. Wasted solids are solids that removed from the reactor due to the limitation of the reactor design and size.

The flow rate of recovery sludge (Q_r) and wasted solids (Q_w) can be determined using Equation 2-10 and Equation 2-11.

$$Q_r = \frac{Q_{in}\cdot(1-\frac{HRT}{SRT})}{(\frac{X_u}{XTSS})}$$ Equation 2-10

$$Q_w = \frac{M\_{xTSS}}{SRT\cdot XTSS}$$ Equation 2-11

2.4 Daily VSS Production Rate Equation

This part lists all the formula used to calculate the mass of volatile suspended solids (VSS) in accordance with substrate removal, kinetic coefficients along with the VSS production. The three sub-parts of produced VSS are originate from heterotrophic biomass, VSS from cell debris and inert biomass. Equation 2-12 used to calculate effluent concentration from anaerobic digestion and Equation 2-13 to Equation 2-16 used to calculate the total Mix Liquor Volatile Suspended Solids (MVSS) generated in the degradation process based on the difference in effluent soluble concentration and influent soluble concentration. Kinetic parameters involved in the equation include; Yield, Endogenous decay rate, maximum specific growth rate and half saturation constant. Yield, *Y*, is the cell yield coefficient that is defined as the mass of biomass (or activated sludge in the term of aeration process) per unit mass of substrate removed (gVSS /gCOD). K_d is the endogenous decay rate per unit of time, usually in the unit of 1 /day. µm is the maximum specific growth rate, and Ks is the half-saturation constant of the Monod equation. The value of K_d and Yield, *Y* are based on two main part of degradation, which are fermentation and methanogenesis. µm and *Ks* are temperature dependent.

Effluent soluble COD concentration

$$C_{eff} = \frac{(K_s.(K_d + \frac{1}{SRT})}{\mu_m - (K_d + \frac{1}{srt})}$$ Equation 2-12

Heterotrophic biomass ($M_{x\text{-}H}$)

$$M_{X\_H} = \frac{Q\cdot(S_o - S)\cdot Y\cdot SRT}{1+K_d\cdot SRT}$$ Equation 2-13

Endogen biomass

$$M_{X\_e} = f_d \cdot k_d \cdot M_{X\_H} \cdot SRT$$ Equation 2-14

Inert Biomass

$$M_{X\_i} = x_{i.in} \cdot Q \cdot SRT/f_{cv}$$ *Equation 2-15*

Where:

C_{eff} = effluent COD concentration (mg/l)

M_{X_H} = mass of VSS produced heterotrophic biomass (g VSS)

M_{X_e} = endogenous biomass (g VSS)

M_{X_i} = inert biomass (g VSS)

K_s = half velocity constant (mg/l)

K_d = endogenous decay rate (1/day)

SRT = Solid retention time (day)

μ_m = Maximum specific growth rate (1/day)

S_o = Total degradable influent COD (gCOD/l)

S = effluent soluble COD (gCOD/l)

Y = biomass yield (gVSS/gCOD)

Q = flowrate (m^3/d)

2.5 Chemical Oxygen Demand (COD)

2.5.1 Fraction of COD in Wastewater

The first major sub-parts of total influent COD are unbiodegradale COD (S_{ui}) and biodegradable COD (S_{bi}) fractions. Biodegradable is divided into soluble readily biodegradable COD (S_{bsi}) and particulate slowly biodegradable COD (S_{bpi}). Unbiodegradable COD consists of two part; soluble unbiodegradable COD (S_{usi}) and particulate unbiodegradable COD (S_{upi}). Figure 2-2 presents fractionation of the total influent COD in wastewater.

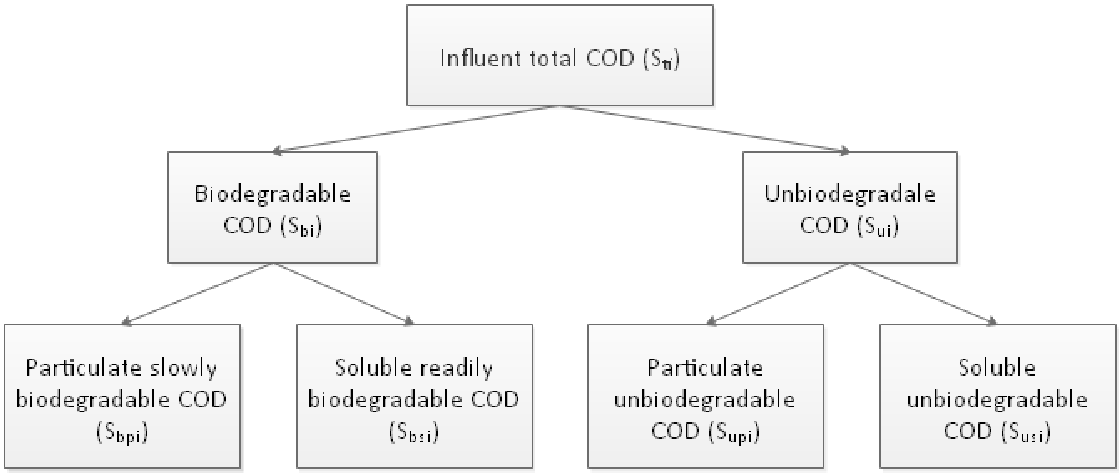

Figure 2-2 Fractionation of total influent COD into its constituent fractions

S_{usi} is the part of the COD that will not get treated in the biodegradation process and will be discharged with the effluent. The S_{upi} is retained in the sludge system. The biodegradable COD fraction is the part of COD that will be degraded by microorganisms and broken down into simple molecules.

2.5.2 COD Correlation with Methane Production

Chemical oxygen demand (COD) directly measures the electrons available in the substrate of organic matter, and is mostly expressed in form of the amount oxygen needed for the substance to be completely oxidized[13]. The number of electrons donated by oxidant is expressed as oxygen equivalent in g O_2/m^3 (see Equation 2-16- Equation 2-17).

$$\frac{1}{2}H_2O \rightarrow H^+ + \frac{1}{4}\,O_2 + e^- \qquad \text{Equation 2-16}$$

$$\frac{1}{4}\,mole\,O_2\,.\;32\,\frac{g}{mole} = 8\,g\,O \qquad \text{Equation 2-17}$$

1 eeq = 8 g COD

The theoretical COD of molecule $C_nH_aO_b$ can be calculated by the chemical oxidation reaction, assuming a complete oxidation that illustrated in Equation 2-18:

$$C_nH_aO_b + \frac{1}{4}(4n + a - 2b)O_2 \rightarrow nCO_2 + \frac{a}{2}H_2O \qquad \text{Equation 2-18}$$

The Equation 2-16 shows that 1 mole of organic matter required $\frac{1}{4}(4n + a - 2b)O_2$mole of O2 or $8(4n + 1 - 2b)\ g\ O_2$. For organic matter containing nitrogen (N), the equation is expressed as:

$$C_nH_aO_bN_d + \frac{1}{2}(2n + 0.5a - 1.5d - b)O_2 \rightarrow nCO_2 + dNH_3 + \frac{a-3}{2}dH_2O$$ *Equation 2-19*

The theoretical COD can be calculated by the oxidation stoichiometry of glucose as expressed in Equation 2-9.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$ *Equation 2-20*

$C_6H_{12}O_6 = 180$ g
$6O_2 = 192$ g
1 gram glucose represents 1.067 g COD (192 g/180 g).

The theoretical COD per unit mass may be different for different chemical compounds. In case of methane, using the equation 2-9, the theoretical COD is shown in Equation 2-21

$$COD_{CH4} = 4gCOD/gCH_4$$ *Equation 2-21*

2.6 Industrial Wastewater Components

Industrial wastewater might have a great variety of components depending on the type of the industry Some components might be present in one type of industrial waste, while some other might not. Listed below are the specific components that become the primary concern in this study.

2.6.1 Ethylene Glycol

Ethylene Glycol or Mono Ethylene Glycol (MEG) is a hazardous compound mostly used as a chemical intermediate in the manufacture of polyesters such as resin, fibers, ink, and coating. Ethylene glycol is also known as 1,2-ethanediol, 2-hydrocyethanol, glycol alcohol, and mono-ethylene glycol or MEG, categorized as a diol compound (Figure 2-3), a compound that has two hydroxyl group.

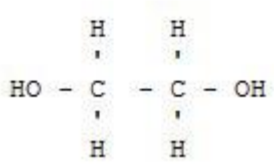

Figure 2-3 Diol structure. The structure contains two hydroxyl group

This clear, colorless and odorless compound was estimated to be greatly released to hydrosphere for the first time during the industrial production in Germany in 1989[14].

Ethylene glycol in general has low toxicity for aquatic organisms[14]. Toxic thresholds for microorganisms are above 1000 mg /liter. A no-observed effect concentration (NOEC) for chronic tests on daphnia is of 8590 mg/ liter.

The degradation process of MEG was studied. Degradation up to 90% or more of the starting concentration was reported in all tests with duration of 1 - 21 days. 92% of chemical oxygen demand (COD) removal and 93% of TOC removal over 24 hours were reported at initial concentration of 172 mg/liter by Matsui et al.[15]. Using activated sludge from a petrochemicals process. 96.8% removal of ethylene glycol was reported using adapted activated sewage sludge from initial COD of 200 mg /liter within 120 hours. A biodegradation rate with a value of 41.7 mg COD /g per hour was obtained [16] [14]. Another treatment by ozone has been reported to remove up to 56% of Ethylene glycol with COD inlet of 500 mg /l within 180 min [17].

2.6.2 Organic Acid

Organic acids are an organic compound that contains both carbon and hydrogen atoms and has acidic properties. The most common example of this compounds includes acetic acid, lactic acid and citric acid, which belong to carbocyclic acid. Acetic acids are commonly used in oil and gas well treatment. Organic acid is also used as a food preservative due to its anti-bacterial substance. Organic acid consumption in poultry has been used for many years to reduce the intestinal bacterial problem[18].

2.7 Biogas Digester Design

This subchapter explains the anaerobic biogas digester types based on its configuration and setting of the reactor. Merits and demerits of each design are explained in details.

2.7.1 Fixed Dome

This type of unit was used in ancient China 2000-3000 years ago. The primary function of the digester is for sewage treatment. From 1920 to the late of the 1980s, China has developed and utilized the biogas digesters. The Government enforces biogas production as an effective use of natural resources to improve hygiene and also to produce energy[8]. Fixed dome biogas digester units have the low construction cost compared to the other type. There are no moving parts and rusting steel parts, with an approximate life cycle in 20 years or more. Fix dome digester construction is buried underground thus affording protection from harsh temperature change such as season change. The disadvantages of this type are the susceptibility to porosity and cracks, fluctuation of gas pressure and low digester temperature. Figure 2-4 shows a comparison between fixed dome digester and floating drum digester. While fix dome has no moving parts, floating drum uses a movable container that reflects the volume and pressure of the gas.

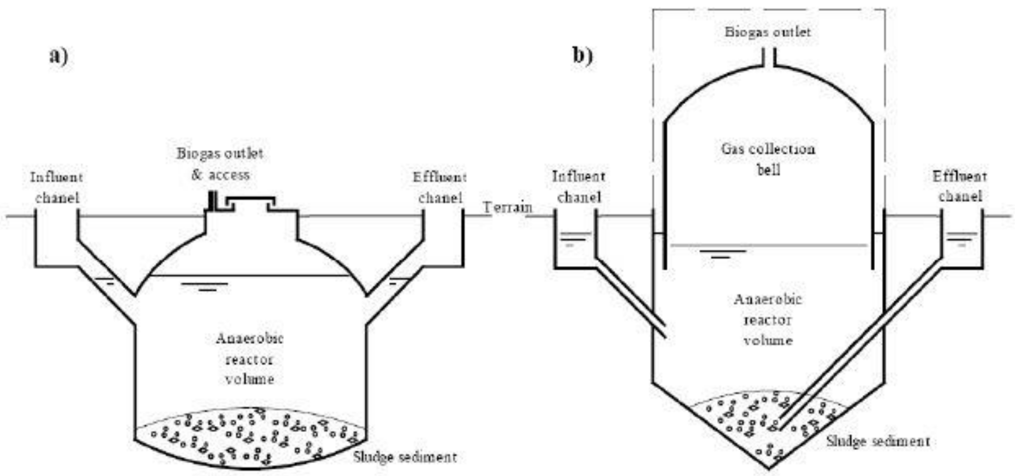

Figure 2-4 Fix dome (a) vs floating drum (b) digester[19]

2.7.2 Floating Drum Biogas

The advantages of this model are in its simplicity, easy operation, constant gas pressure and volume of stored gas that directly visible by the movement of the drum. It is well known and widely used in India for centuries. This model is mostly used to treat the wastewater, while the gas is mostly used directly for cooking and lighting[8].

Floating drum has a higher construction cost due to its moving parts. The use of steel inside of the digester also makes its component liable to corrosion, resulting in short life up to 15 years. Regular maintenance is required to coat/paint the components to prevent the corrosion. In spite of these disadvantages, floating-drum plants are regularly recommended in cases of doubt. Water-jacket plants are universally applicable and especially easy to maintain. The drum will not stick, even if the substrate has a high solids content. Floating-drums made of glass-fiber, reinforced with plastic and high-density polyethylene were successfully built, but the construction cost is higher than with steel.

2.7.3 Covered Lagoon Digester

The special surface covers are secured around the pond sometimes by burying in a perimeter trench or by anchoring to a concrete perimeter curb. Covered lagoon digesters use covers that made from high-density polyethylene or polypropylene, and some of these materials have a lifespan of more than 15 years and can also be repaired easily. Baffle system installed inside the lagoon digester to help mix the liquid substrate. It suitable to treat substrate wastewater with very high COD concentration. Detention times ranged between from 20 to 50 days with lagoon depth of 5 to 10 meters [19]. SRT for lagoon digester will be higher than the detention time because the large fraction of influent solids will undergo long-term degradation. SRT estimated value of covered lagoon can vary from 50 to 100 days [9]. Figure 2-5 show the covered lagoon digester where effluent treated by post-treatment.

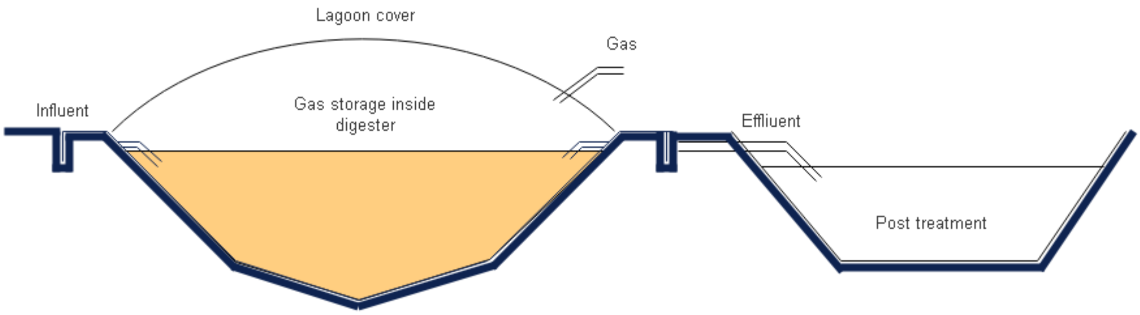

Figure 2-5 Covered lagoon digester with post-treatment in effluent

A covered lagoon digester has some distinct advantages; mainly it is lower costs to build and operate. The downside is the seasonal variation in biogas production as most systems rely on ambient temperature and in the colder months, less methane is produced[20].

2.7.4 Horizontal Digesters

Small biogas plants often use horizontal design. The old or used tank can be used as the material for this design to reduce the cost. The tank then is reconstructed with central shafts and mixer arm. Tank for digester in this design has a standard volume between 50 and 150 m3. The width can vary around 3.2 to 3.5 m. Hydraulic Retention Time (HRT) for this design is between 40 and 50 days[21].

The input substrate is first heated and mixed with the mixing arm until reaching mesophilic temperature. This digester is suitable for small farm, with the low-cost budget (Figure 2-6).

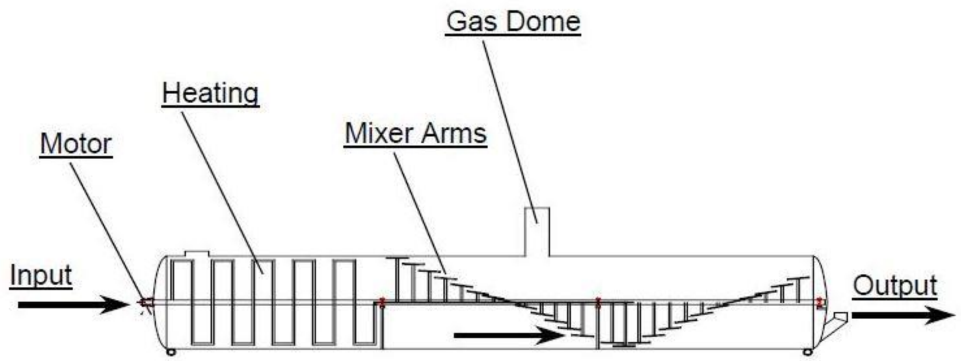

Figure 2-6 Horizontal Digester[21]

2.7.5 Anaerobic CSTR (Continuous Flow Stirred-tank Reactor)

CSTR is a tank in which the liquid inside is mixed with an agitation system. The standard type of CSTR digester used in German is presented in Figure 2-7. It is constructed with concrete with the size between 500 and 1,500 m3. The height is around 5-6 m, and diameter varies between 10-20 m.

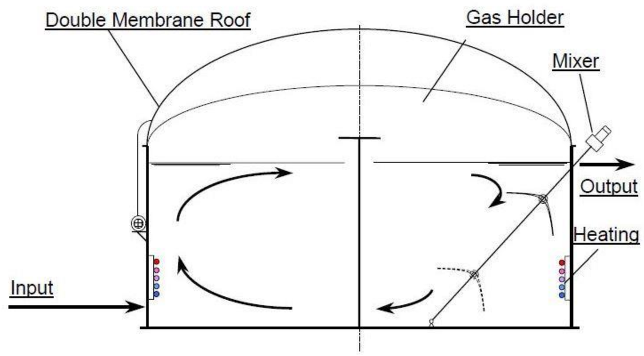

Figure 2-7 Standard CSTR digester with internal blade agitator and heat blanket[21]

The heating system in the tank delivers hot water into tubes fixed along the wall-like blanket surrounding the tank. The mixer can be one unity with the tank or equipped with a motor and located outside of the tank. The agitation system can be divided into three categories: gas injection system, mechanical stirring system and mechanical pumping system (Figure 2-8). Using a combination of agitation system increase efficiency of mixing inside the digester compared to single agitation system.

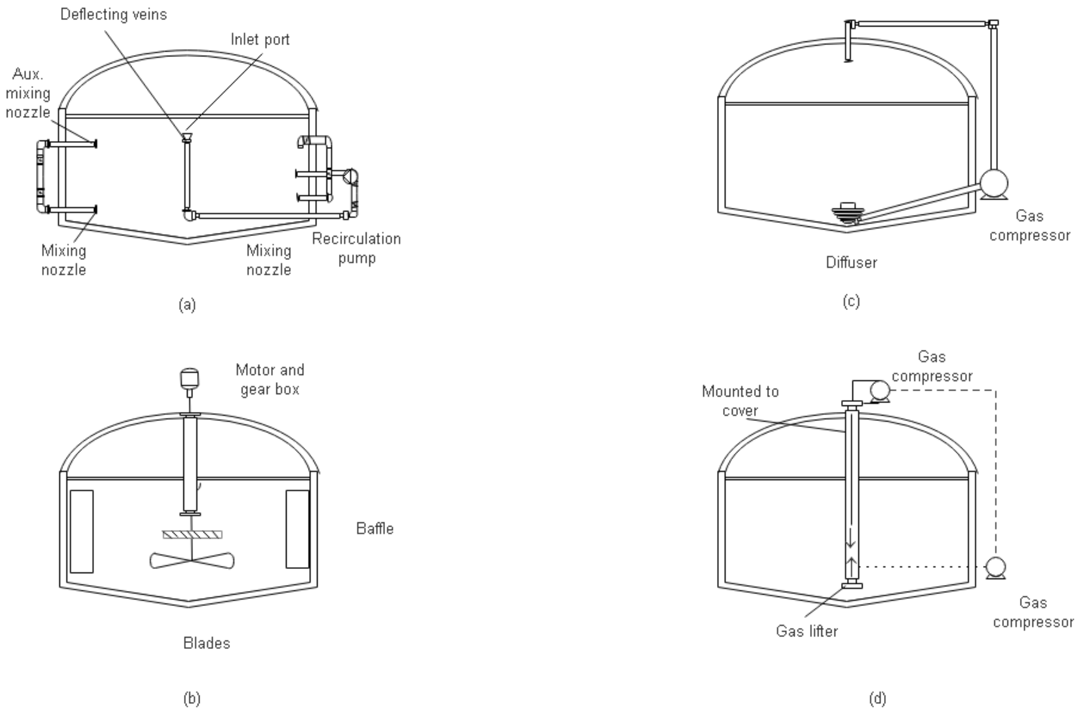

Figure 2-8 CSTR mixing agitator system: mechanical pumping system (a), mechanical stirring system (b), unconfined gas injection system (c), confined gas injection system (d).

The gas holder consisting of two layers is located at the top of the tank. The inner layer is the flexible gas holder, and the outer layer is for weather cover and in fixed shape. The substrate used for this type of digester can vary, as long the flow rate is low enough. The average input per year for this digester is 10,000 m3 per year.

2.7.6 Anaerobic Contact Process

The Anaerobic Contact process is a model modified from CSTR type digester. It recycles back the sludge from the effluent into the digester to increase the SRT. Anaerobic contact process overcomes the disadvantages of CSTR model. By separating the HRT and SRT values, the volume of the mix digester can be reduced[22]. Figure 2-9 shows the schematic flow of Anaerobic Contact Process.

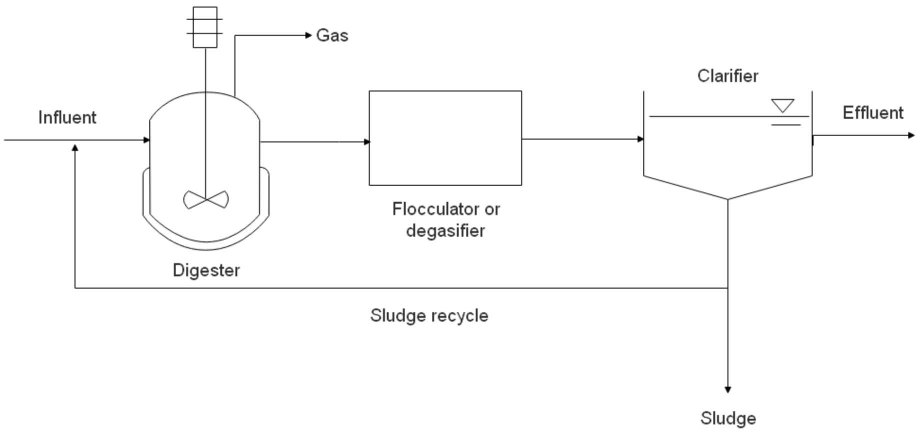

Figure 2-9 Anaerobic contact process, part of the sludge recycled back into the digester.

Most common systems for the solids separation use gravity based clarifier, but a filter membrane can also be used when the sludge has low settling velocity. Figure 2-10 shows the process flow of a membrane separation technique in an anaerobic digester. Membrane separation system provides a separate solids technique by almost capture all the solids and recycled back into digester tank. It increases the efficiency of digesting process by increasing the time needed to process VFA and biodegradable COD of the wastewater. The effluent quality is also increased compared to gravity based clarifier.

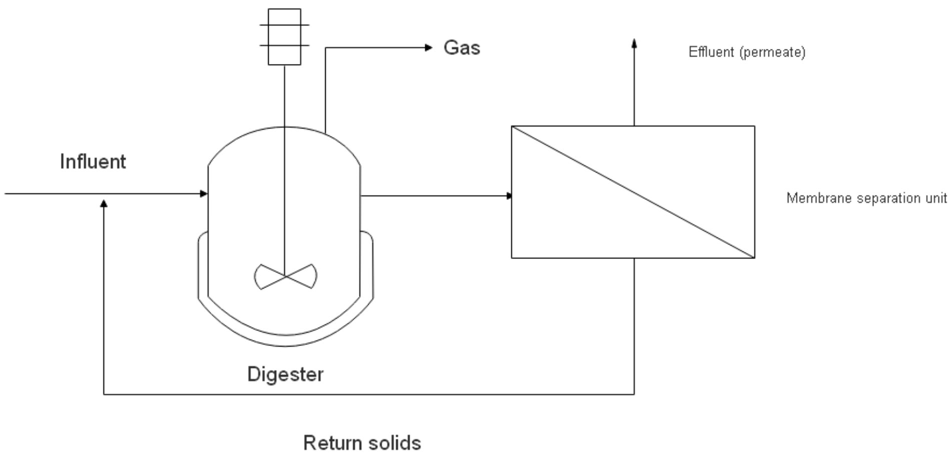

Figure 2-10 Anaerobic system with external membrane separation

One of the disadvantages of membrane separation system is the membrane fouling and the power consumption of the pump system. Organic fouling problem is the most common thing occurring in this system. The fouling is caused by the accumulation of colloidal material and bacteria on the surface of the membrane[22].

2.7.7 UASB (Up-flow Anaerobic Sludge Blanket)

Up-flow anaerobic sludge blanket reactor is the anaerobic reactor most widely-used in the world for treating several types of wastewater[23]. Invented by Lettinga in late 1970, the UASB became one of the most notable of development in anaerobic system. In the UASB reactor its wastewater inlet flows from the bottom of the reactor with the pre-determined setting of up-flow velocity. The inlet stream will hit the sludge blanket consisting of concentrated granules in the bottom part of the tank. The system is suitable to treat wastewater contain less than 6 % of solids. Figure 2-11 shows the original design of UASB reactor without effluent recycling process or packing filters (a) and UASB with recirculation pump (b). The UASB reactor design is divided into several height fractions, and each fraction contains separation unit. The separator helps remove solid with the liquid.

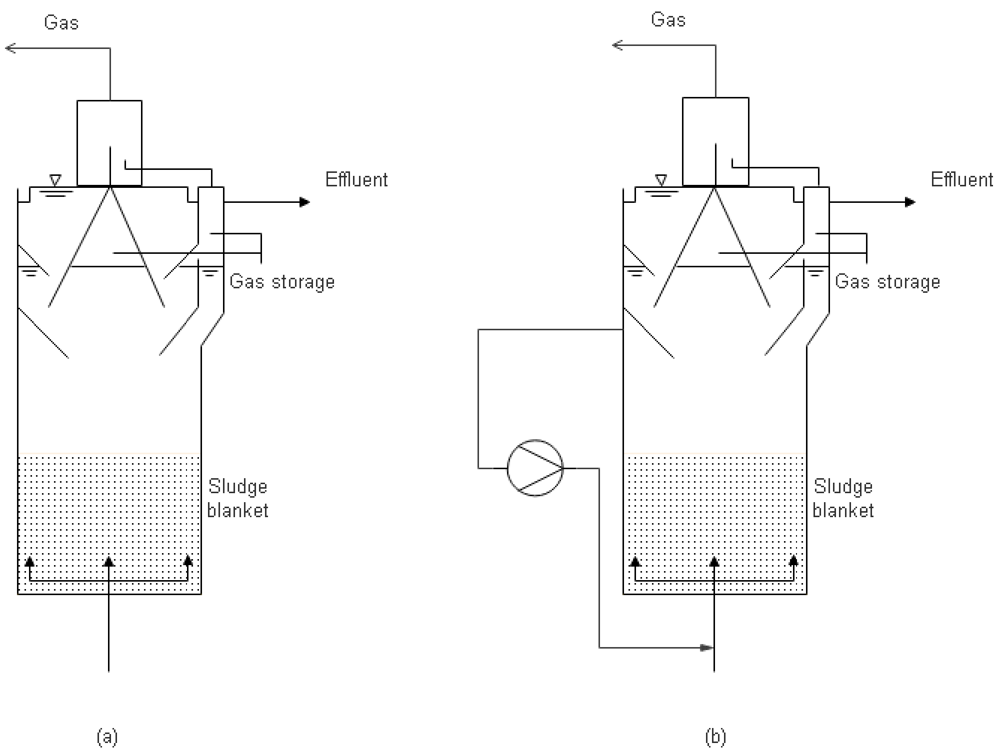

Figure 2-11 Up-flow anaerobic sludge blanket reactor. Original design (a); UASB with recirculation pump (b)

The formation of granules plays an important role in the UASB system. The blanket zone is formed above the suspended biomass zone. This zone acts as the separator between liquid flowing up and the sludge below. The advantage of the UASB reactor is that requirement of sludge disposal process is reduced compared to another anaerobic digester model [24]. The UASB system allows the use of high volumetric COD loading compared to another process.

The up-flow velocity is determined based on reactor area and the flowrate. For wastewater with low concentration of soluble COD, the up-flow velocity can follow the recommended design parameter adapted from Lettinga and Hulshoff (Table 2-1), but for wastewater with high COD it will be determined by the volumetric organic loads to the reactor.

Table 2-1 Up-flow velocities recommended for UASB rector[25]

COD in wastewater type	Up-flow Velocity (meter/hour)	Typical reactor height (meter)
nearly 100% COD	1.0-3.0	8
partially soluble	1.0-1.25	6
municipal wastewater	0.8-1.0	5

2.8 Pre-Treatment of Methane Production

Pre-treatment of biogas is known to increase the efficiency of biogas production. It can be classified into three categories; thermal treatment, mechanical treatment and thermochemical treatment. However, overall the methods presented until now have their drawback and does not have breakthrough[26]. Mechanical pre-treatment often appears to require high capital cost and consume high energy in the process, while the thermal treatment requires high temperature to get significant improvement. The pre-treatment methods and their merits are listed in Table 2-2.

Table 2-2 Pretreatment method for biogas production. Listed estimated cost, merits and demerits of the method[26]

Method	Estimated cost (EUR/tonne TDS)	Advantage	Disadvantage
Thermal	200		low yield, dependent on sludge type
Oxidation	800	High disintegration effieciency	Low pH. High cost
Thermochemical	Not available	Simple	Corrosion, odour
Ball mill	3000	High efficiency, simple	High operation cost
Ultrasound	833	Complete disintegration	Energy intensive

2.9 Energy Utilization from Wastewater

Biogas production from a differents source type was calculated under ideal condition. The data were obtained from biogasworld website (https://www.biogasworld.com/biogas-calculations). The SRT for the calculation was estimated ~ 40 days. Table 2-3 shows the estimated biogas production, electricity, and heat generated from a different type of wastewater.

Table 2-3 Biogas production from different type of wastewater

Waste type	Total solids	Volatile solids	Biogas production	Electicity generated	Heat generated
	%	%	m^3/d	kWh	GJ/year
WWTP Sludge	5	80	360	262,800.00	1,131.00
municipal (wet)	13	90	1680	1,208,880.00	5,200.00
Fats, oils, and grease (FOG)	36	84	9048	6,508,680.00	28,101.00
Cow slurry (dairy)	8	80	504	359,160.00	1,551.00

note:
WWTP: wastewater treatment plant
Feed: 10000 tons/year
Digester type: wet
Biogas usage: CHP (Combined heat and power)

2.10 Focus of the Research

Many biogas installations were successfully implemented, whether using solid bio-waste or wastewater. Biogas installations can have a wide variation in term of design, depending on substrate and the requirement for optimal conditions. This study is aimed to propose the optimal biogas design parameters satisfying the requirement of *Norwegian Technology AS* for treating the wastewater from selected industries and producing biogas. To achieve this objective, literature study of the design was carried out to seek the advantage and disadvantage of different bio-digester designs. Analysis of information regarding used coolant wastewater sample, which assumed contain bio-pesticide, was also in focus. The possible best available technology is analysed in detail including the estimated capital cost required. The cost analysis of the technology is carried out to give the risk and gains of design. In the term of cost, the analysis includes the estimated capital cost to build a digester design as well as the operational electricity consumption reviewed.

3 Materials and Methods

This chapter describes the methods used for calculating and analyzing bio-digester design for Anaerobic Contact and UASB (up flow anaerobic sludge blanket digestion). Both of the digester types are compared and analyzed based on design merits and demerits, and their estimated capital cost production. A schematic of the design is presented in the form of process flow based on author preferences. Volume, SRT, sludge production, estimated maximum daily methane production, nutrients requirement and mechanical design were calculated based on journals and books form literature study. The substrate selected in this project is glycol base compound (ethylene glycol and propylene glycol), and some organic acids. The wastewater substrate from industry was also tested for its biodegradability using biogas batch test and its properties, such as COD, solids content and ion content. Four different samples of wastewater tested during the laboratory experiment, which are contaminated MEG (mono-ethylene glycol), used coolants, and two different slop water. All laboratory works for this master's thesis were conducted at the University of Stavanger. Figure 3-1 shows the flow chart used in this study.

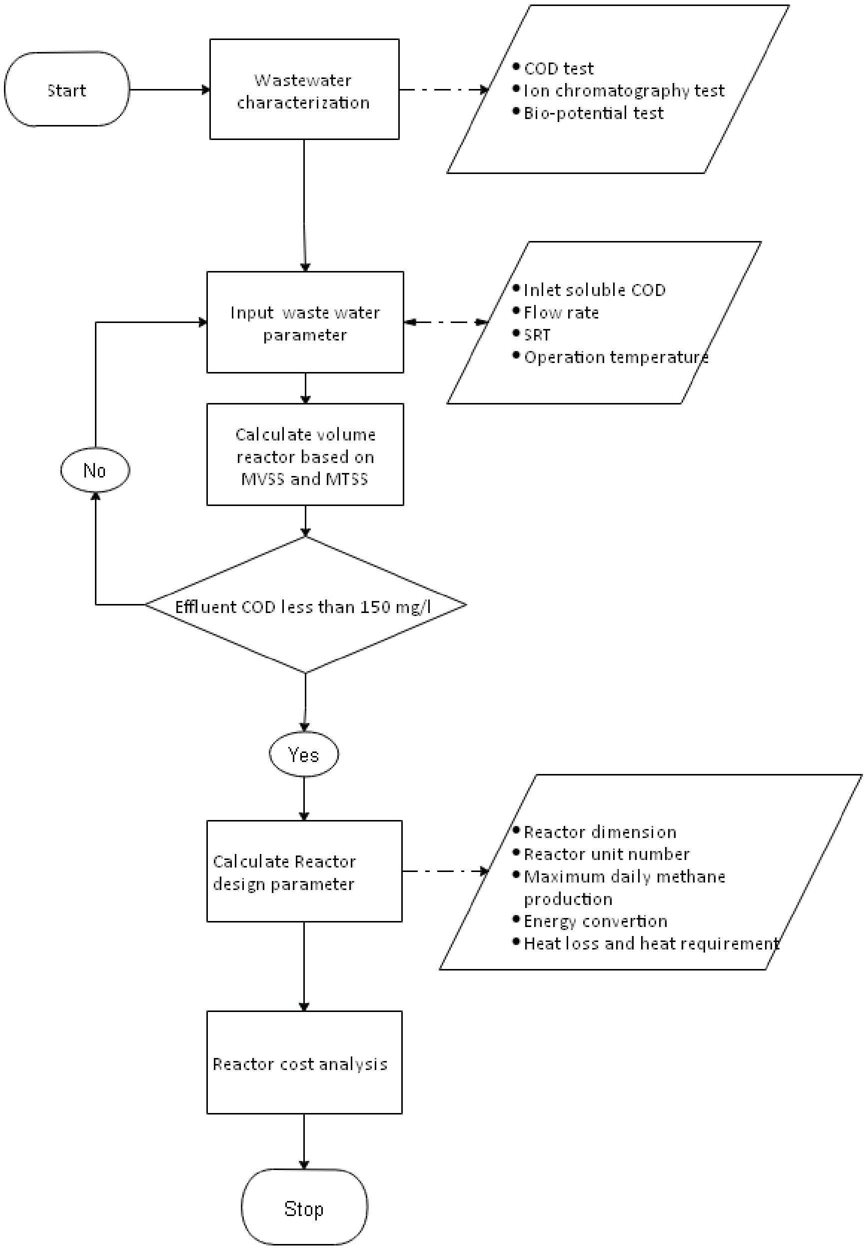

Figure 3-1 Research flowchart

3.1 ANAEROBIC CONTACT and UASB Design Calculation

The procedure for calculating the physical design of the digester was following this order: 1) calculate the SRT based on the pre-determined target effluent soluble concentration; 2) acquiring suitable SRT, sludge mass produced from substrate and bacteria determined; 3) the volume is calculated based on the pre-determined MLSS setting. Basic assumption made for the calculation was, the soluble COD in the wastewater is bio-degradable. Maximum daily methane production rate and energy generated by the methane were also computed. Wall thickness of digester design is calculated based on the type of material used.

3.1.1 Pre-Determined Parameters of the Calculation

The substrate type to be treated in this designed digester is glycol-bases compound (ethylene glycol and propylene glycol) and some organic acids. Maximum average COD in the wastewater inlet to the digester is set to 70 kg/m^3. For this design setting industrial wastewater which contains more than the average COD will be diluted to reach allowable COD parameter. Table 3-1 provides the pre-determined properties of the wastewater substrate and system operation used for the design calculation.

Table 3-1 Pre-determined properties and system operation for the anaerobic digester design calculation

Properties	Value	unit
Average Influent flow	150	m^3/d
Max hourly influent flow	9.4	m^3/h
Average influent soluble COD	70	kg/m^3
MLSS for Anaerobic Contact system	4.0	kg/m^3
MLSS for UASB	30.0	kg/m^3
Operation temperature	35	°C
Effluent soluble concentration	< 500	mg/l

3.1.2 Mass Balance Calculation

The COD fraction availability data of the wastewater substrate is limited in the calculation. Thus the biodegradable COD and non-biodegradable COD part of it can only be predicted based on assumption. The assumptions used are 99 % of soluble inlet COD is degradable and 1 % of inlet soluble COD is un-degradable.

3.1.3 Maximum Daily Methane Production and Energy Conversion

The calculation of daily methane production is based on the difference in total degradable influent COD and effluent COD. Biogas production rate used in the process calculation is 0.4 l CH4/ gram of CODTSS. The ratio used is based on the COD mass balance of the bio-process. The energy conversion calculation is based on of energy density of methane at a specific temperature. Table 3-2 shows the values and unit used for methane production and energy conversion.

Table 3-2 Parameter used for methane production and energy conversion

Parameter	Value	unit
Biogas temperature	30	°C
Biogas production ratio	0.39	l/g COD
Methane ratio in biogas	65	%
Methane energy density	50.1	kJ/g
Methane density at 30 °C	0.635	g/l

3.1.4 Wall Thickness Calculation

Wall thickness of the primary digester is calculated based on the static and working pressure given by the biomass inside of the primary digester. The material used as the digester's wall is affecting the minimum wall thickness calculation. In this project carbon steel is selected as digester material. Table 3-3 below describes considered allowable corrosion used in the calculation.

Table 3-3 Parameter used for wall thickness calculation

Parameter	Value	unit
working stress of carbon steel	94408	KN/m2
Joint Efficiency Ej	0.85	
Internal radius r_i	3.4	m
corrosion allowance	2	mm

3.1.5 Process Flow Diagram

A process flow diagram was build based on the digester unit design calculation and properties of the inlet wastewater coming to the anaerobic digester. Pre-treatment used for the wastewater includes grit removal and DAF (Dissolved Air Flotation) unit. Equilibrium tank is suggested as flow control of the wastewater coming to the anaerobic digester. The digester is split into two tanks due to the acidification process and gasification process for Anaerobic Contact type digester. Membrane filter unit is selected as sludge recycle unit from the primary digester. As an alternative, clarifier with sludge thickening unit suggested. The effluent of the digester unit was treated using aeration unit to achieve standard disposable wastewater. The process flow diagram is presented as a part of the Results section.

3.2 Laboratory Test

This part explains the laboratory scale experiment of anaerobic treatment for four different types of sample collected from wastewater tank, *Norwegian Technology AS*, Stavanger. Table 3-4 provides the samples used for the study. The computerized batch test was used in the trial to find the bio-degradability of the components in samples. The inoculum bacteria used in this study was collected from line production of IVAR Grødaland. COD and ion content properties of the collected wastewater were tested to support the bio-potential results from the anaerobic batch test. Ion content of the samples were tested using ion chromatography technique. The standard method used for wastewater characterization is based on the modified method listed on American Water and Wastewater Association (AWWA)[27].

Table 3-4 List of the samples tested in the study including its primary component

Sample name	primary component
Contaminated mono-ethylene glycol	glycol
Slop water A	a mix of unknown chemical
Slop water B	a mix of unknown chemical
Inoculum	a mix of granule solids and microorganisms
Used coolants	glycol

3.2.1 Biogas Potential Test in Batch Reactor

The biogas potential was tested using AMPTS II (Automatic Methane Potential Test System II). The instrument developed by BPC (Bioprocess control) consist of four main parts; incubation unit, CO_2 absorber unit, gas counter unit and AMPTS II software. Figure 3-2 shows the configuration of AMPTS II unit implemented for investigating the biogas potential, using sludge as inoculum. The operational temperature used for the test was 35 °C using water bath controlled electronically by the incubator unit. The CO_2 absorber unit prepared for the test is NaOH 3 M and 0.4 % Thymolphthalein pH-indicator solution. All the CO_2 produced from the batch was assumed to be absorbed by the absorber unit, and thus the gas counted in the gas counter unit was assumed to be pure methane. Although H_2 gas is produced in the anaerobic biodegradation process, for the gas volume conversion it is assumed that the methane is pure, as the biogas pass through the absorber. The gas counter unit uses standardized metal ball weight connected to a plastic bar which blocks the biogas flow. When each ten µl of biogas accumulates, the plastic bar is lifted by the biogas pressure and sends signals to the AMPTS II software. Methane flow rate and volume data were collected online during the test.

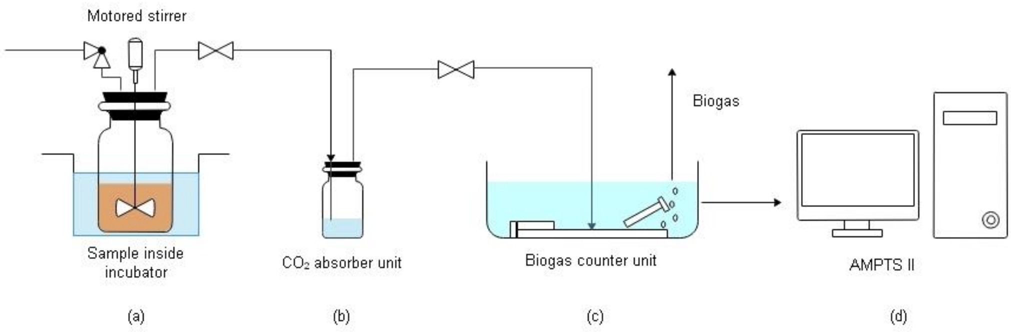

Figure 3-2 AMPTS II configuration unit consist of incubator (a), CO_2 absorber unit (b), Biogas counter unit (c) and AMPTS II software (d)

The batch test was conducted for 14 days (2nd - 15th April 2017) and used the setup as mentioned below (Table 3-5). The inoculum was collected from IVAR Grødaland's line of the bio-process.

Table 3-5 The setup used for biogas batch test

Batch Jar number	Component content
1 2	100 ml MEG + 150 ml sludge
3 4	100 ml coolants + 150 ml sludge
5 6	100 ml slop A + 150 ml sludge
7 8	150 ml sludge+ 100 ml water
9	100 ml filtered coolants + 150 ml sludge
10	50 ml filtered coolants + 100 ml sludge + 50 ml water

3.2.2 COD Measurement

Total COD and filtered COD of the samples were tested for analysis and used as a reference for the anaerobic digester design calculation. COD test used COD test kit as part of the spectrophotometer measurement. COD test kit product number used is PN 109773 (range COD concentration between 100-1500 mg/l), and the spectrometer used for this study is Spectroquat Pharo 300 (Figure 3-3).

Figure 3-3 Spectroquat Pharo 300 instrument.

The procedure of COD test was carried out based on the COD test kit manual. 2.0 ml of diluted sample is added into the test kit tube and mixed using vibration test tube shaker (HEI-036130000), then the tube was incubated in incubator unit (TR 620), at 148 °C for 2 hours. After that the tube was cooled until it reaches room temperature. Then the tube was inserted into the spectrometer to measure COD based on the method selected on display.

3.2.3 Ion Chromatography Test

The content of ions dissolved in the samples were analyzed using auto sampler ion chromatography instrument (DIONEX ICS-5000, Figure 3-4). Sodium, magnesium, potassium and sulfate ions were the components tested due to their influence on inhibition process of anaerobic biodegradation.

Figure 3-4 Dionex ICS-5000 series instrument.

The samples were filtered using a 1.5µm filter (VWR Ca. 516-0876) and diluted by 500 and 1000 times before injected into ion chromatograph instrument. The injected samples were carried out by the carbonate/bicarbonate solvent in elution process through the chromatography column. The components, which have ion properties, were affected by the opposite polarity of the column (cation ion exchange used for this test) and retained longer in the column based on their ionic strength properties. The more the ionic strength of the component, the more the component retained in the column. The detector measures the polarity change in the effluent resulting in a graph containing peaks with a different retention time for each component. Standard references (Sea water reference and Low salinity reference) were created (Table 3-6) and used to measure the ionic composition of samples. The concentrations of the ions were acquired by comparing the area produced from the sample and the standard reference.

Table 3-6 The ion concentrations in standard reference samples used for ion chromatography analysis

Component	Sea water reference		Low salinity reference	
	C(mg/l)	C (μmol/l)	C (mg/l)	C (μmol/l)
Ca^{2+}	521	13.00	88.00	2.1957
Mg^{2+}	1663.8	68.46	77.10	3.1722
Na^{+}	919	399.76	121.90	5.3025
Cl^{-}	18625	467.66	611.37	12.2585
$SO4^{2-}$	2306	71.92	73.60	2.2953
K^{+}	394	10.08	77.00	1.9694

3.3 Capital Cost Analysis

The capital cost analysis includes comparison of two reactor models. The main objective of the analysis is to quantify the total cost of ownership of the product. The construction cost of the reactor tank is based on its constituent material calculated including the pump and piping required for the construction. Capital cost estimation data was carried out by using different data collected from websites.

The major cost elements included in LCC (Life Cycle Cost) are the capital cost, operating cost, the cost of deferred production and disposal cost. The only cost analysis conducted in this study is a capital cost which is included in CAPEX (capital expenditure).

4 Results

In this chapter, results obtained from the study were presented in four-part; (a) the design calculation for Anaerobic Contact, (b) the design calculation for UASB, (c) process flow diagram and (d) laboratory experiments test for bio-potential. For design calculation part, all the data have been summarized in figures and table while raw calculations are presented in the Appendix. Design calculation consists of two main parts; Anaerobic Contact reactor and UASB reactor. Process flow diagram presented in this chapter is for using Anaerobic Contact as the main digester.

4.1 Anaerobic Contact Design Parameters

Anaerobic Contact design and calculations are divided into four parts, which are; the calculation of biomass inside the reactor, maximum daily methane gas production rate, reactor wall thickness and thermal heat energy required for heating the process. Summary data of the Anaerobic Contact design calculation is presented in Table 4-1, while the detailed calculation is presented in Appendix 1: Table A- 2 - Table A- 5.

Table 4-1 Design parameters calculation results for Anaerobic Contact reactor

Design parameter	Unit	Value
Acid phase SRT	day	3
Acid phase MVSS	kg	2860.0
Acid phase MTSS	kg	3575.0
Acid phase reactor volume	m^3	1526.0
Acid phase reactor diameter	m	18.0
Acid phase reactor height	m	6
Gas phase reactor SRT	day	26
Gas phase MVSS	kg	11503.8
Gas phase MTSS	kg	14379.8
Gas phase reactor volume	m^3	5941.7
Gas phase reactor diameter	m	28.0
Gas phase reactor height	m	9
Total solid retention time (SRT)	day	29.0
Total Sludge production	Kg /d	1745
Total volume liquid for 2 phase	m^3	4489
HRT from primary gas tank	days	26
Recovery flowrate, Qr	m^3 /day	67.04
Sludge Recovery ratio, R		0.45
Q waste from clarifier (xu= 12000 kg/m^3)	m^3 /d	46.1

Methane production per day	m^3 /day	4129.9
Total gas Produced per day (65 % methane)	m^3 /day	6353.8
Energy produce	MJ /day	131305.6
Nutrients Nitrogen addition	kg/d	178
Nutrients Phosphorous addition	kg/d	35.6
Clarifier diameter	m	2.8
Clarifier height	m	2.2
Clarifier Total height including sludge base	m	3.2
Maximum allowable pressure inside tank	kPa	389.3 for gas phase and 349.4 for acid phase
Digester wall thickness	Mm	19 for gas phase and 17 for acid phase
Pump power for recirculation	KW	50+15

4.1.1 MVSS Production Inside of Digester

The Table 4-1 shows the results of design calculation of Anaerobic Contact. To find suitable SRT based on the pre-determined properties of wastewater, listed in Table 3-1, MLSS used in the calculation is 4000 g /m^3. Based on the criteria of effluent concentration coming out from the digester, minimum SRT with effluent COD concentration less than 150 mg /L is selected and SRT recommendation for Anaerobic Contact reactor is around 30-50 days. For the purpose of maintaining more solids produced inside the reactor, SRT of 29 days selected. The consideration of selecting SRT of 29 days is based on the reactor volume. The higher SRT value selected, the higher cost of construction of digester due to waste volume to be treated.

The reactor volume selected from SRT then split into two part of reactor based on acid /gas phase digestion. A common value of SRT selected for the acid phase is between 1 to 3 days. In calculation for this study, SRT of acid phase is three days thus the gas phase SRT is 26 days. Design parameters used in the acid phase and gas phase are shown in Table 4-2. This data is acquired by splitting the process into fermentation and methanogenesis. Both acid phase and gas phase use mesophilic temperature operation. MVSS and MTSS are calculated for both acid phase and gas phase using different SRT value. MVSS of the degradation process is acquired by calculating the biomass produced by heterotrophic bacteria and endogens cell debris.

Table 4-2 Parameter used in Acid phase and Gas phase

Design parameter	Unit	Gas Phase Value	Acid phase Value
Solid yield Y	gVSS /gCOD	0.04	0.1
f_d (fraction of decay)	gVSS cell /g VSS decay	0.15	0.15
Maximum specific growth rate (µm)	gVSS /gVSS.d	0.35	3.5
Ks	mg /l	160	160
Decay coefficient (K_d)	gVSS /gVSS.d	0.02	0.04

The minimum liquid volume inside of the tank is calculated based on MTSS produced in selected SRT and MLSS of 4 kg /m^3. Reactor volume for acid phase and gas phase are calculated and listed in Table 4-1. A conversion factor of 1.2 was used to calculate the total volume of the digester. This factor is used to consider the dead volume inside of the digester. Reactor dimensions, such as height and diameter, were calculated based on ratio 5:20. Table 4-3 shows the comparison of the parameters calculation results of acid phase and gas phase including reactor dimension and biomass produced.

Table 4-3 Comparison between acid phase and gas phase design parameter

Design parameter	Unit	Acid Phase Value	Gas phase Value
Solid retention time (SRT)	day	3	26
Sludge produce (P_x)	Kg /d	1192	553.1
MVSS	kg	2860.0	11503.8
MTSS	kg	3575.0	14379.8
Volume liquid required	m3	894.7	3594.9
Volume effective	m3	1072.5	4313.9
Diameter of digester	m	18.0	29
Height of digester	m	6	9
Total digester Volume	m^3	1526.0	5941.7

Sludge recovery ratio was calculated based on the Equation 2-10 and Equation 2-11. Q waste value is obtained from two different spot locations of the wasting process; main digester and clarifier. Waste from bio-reactor has the same MLSS concentration which is 4000 g /m^3, but MLSS from clarifier has been thickened and assumed has a concentration of 12000 g /m^3.

4.1.2 Nutrient Addition

The amount of nutrients needed for the reactor was calculated based on the daily MVSS production from the digester. In this case biomass from acid phase and gas phase tank is summed up to get total MVSS produce. Nutrient requirements were calculated based on 12% of MVSS for nitrogen and 2.4 % of MVSS for phosphorous. 178 kg /d of nitrogen and 35.6 kg /d of phosphorous are required in this case (Table 4-1).

4.1.3 Daily Gas Production Rate

Quality and quantity of methane produced in the bio-process depend on the operational temperature set on the digester. Based on the Equation 2-10, methane ratio are 0.4 L /g of degraded COD at 35 °C. The temperature assumption of methane gas for this study is set at 30 °C, thus the methane ratio produced are 0.39 L /gCOD. Energy produced from the methane was calculated based on the standard energy density of methane at 30 °C[9]. Table 4-1 shows the value of maximum daily methane and biogas production and the energy obtained from it. Methane ratio in the biogas is assumed to be 0.65.

4.1.4 Reactor Wall Thickness

The reactor wall was assumed to be built by carbon steel metal, and the thickness of the reactor metal was calculated based on the static pressure from the liquid inside digester and working pressure of it. The working pressure of the digester is calculated as standard atmospheric pressure, while the static pressure depends on the MLSS setup of the digester. A conversion factor of 1.33 is used to calculate maximum allowable pressure inside the tank. The maximum allowable pressure calculated in this case is 389.3 kPa. A previous study mentioned a range of pressures used in the digester reactor between 101.321 kPa and 101321.5 kPa [28]. The calculated value of wall thickness for the primary digester e is 31.08 mm including the consideration of corrosion with 2 mm thickness.

4.2 UASB Design

As a comparison to the ANAEROBIC CONTACT design, the UASB parameter design was computed with a similar step to the Anaerobic Contact design. Table 4-4 compares the ANAEROBIC CONTACT design parameter result with UASB design.

Table 4-4 Comparison of UASB and Anaerobic Contact parameter design

Design parameter	Unit	UASB	Anaerobic Contact
		Value	Value
Solids Yield, (Y)	gVSS /gCOD	0.08	0.08
f_d (fraction of decay)	gVSS cell /g VSS decay	0.15	0.15
maximum specific growth rate (µm)	gVSS /gVSS.d	0.35	0.35
K_s	mg /l	160	160
Decay coefficient (K_d)	gVSS /gVSS.d	0.03	0.03
MLSS	g /m^3	30000	4000
Temperature	Celsius	35	35
Solid retention time (SRT)	day	50	29
MVSS	Kg	37785.6	14363.8
MTSS	kg	47232.0	17954.7
Sludge produce (P_x)	kg/d	945	1745
Volume of reactor required for liquid	m^3	1574	4489
Total number of reactor		4	2
Reactor diameter	m	9	18 for acid phase and 29 for gas phase
Reactor height	m	10	6 for acid phase and 9 for gas phase
Total digester tank volume (all unit)	m^3	2544.7	7467.7
Methane production per day	m^3 /day	4130.3	4130.0
Total gas Produced per day	m^3 /day	6354.3	6353.8
Energy produce	MJ /day	131315.8	131305.6
N required	kg /d	96.4	178
P required	kg /d	19.3	35.6
Max allowable pressure inside Digester	kPa	406.5	389.3 for gas phase and 349.4 for acid phase
total wall thickness	Mm	20.0	19 for gas phase and 17 for acid phase
Recirculation pump power	kW	15	50 for gas phase and 15 for acid phase

The reactor tank for UASB is not divided by acid phase and gas phase like in the Anaerobic Contact model. As it says in Table 4-4, UASB reactor is set into four main tanks set in parallel. This setup is based on the reactor efficiency, which is not allowed the size more than 500 m^3 per tank. The calculated data showed that each of the UASB tanks has 636.2 m^3 of volume with 9 m in diameter and 10 m in height. The height of the reactor was added to accommodate gas volume inside, the height range commonly used is ~ 2.5-3.5 m. In this calculation, 8 m of tank height is used as a basic standard to determine the diameter of the tank based on the assumption that the COD in the influent are COD that nearly 100 % soluble[9].

The volume of the UASB reactor is calculated based on MVSS biomass produced and SRT setting. The SRT setting for the UASB is in the range of 50 - 100 days. In the calculation, SRT of 50 days was selected. Different approaches were used to calculate the height of anaerobic contact process bio-reactor and UASB bio-reactor. In Anaerobic contact reactor the height was selected based on design ratio of 5:20 in height over diameter, but for UASB reactor the height was selected based on typical nominal height used based on COD criteria (Table 2-1). Size of UASB digester tank is 0.34 times smaller compared to Anaerobic Contact tank, based on the calculated data in Table 4-4. The value of wall thickness required in UASB reactor is higher than for the Anaerobic Contact unit reactor, 20 mm and 19 mm respectively. The difference in wall thickness is due to static pressure from MLSS used in each digester type.

4.3 Heat Transfer for Operation

In this part, the heat required for starting up the digester and the heat for maintaining the temperature during the operation are calculated. Heat transfer rate during start-up is obtained by adding up 3 components of heat transfer in this process;

- Heat required to increase the temperature of the liquid inside the tank,
- The heat to increase tank material temperature and
- The heat loss from the tank.

Inlet wastewater is assumed to be 20 °C before entering digester. Table 4-5 shows the comparison values of heat required to reach an operational temperature in Anaerobic Contact and UASB. The energy consumption was calculated based on heat loss from metal frame digester. Concrete heat loss can be calculated by set specific value of heat transfer coefficient of concrete.

The energy consumption for total mean heat transfer required during start up if the reactor heat up time set at 5 hour is 8133 kW (Acid phase and Gas phase) and 741 kW for Anaerobic Contact and 1 unit of UASB, respectively. Total energy consumption during startup of UASB is 2964 kW (from 4 units of UASB). If the energy consumption considered too high, the heat up time can be increased to lower it, but the consequence is in the time delay of the startup operation.

Table 4-5 Rate of heat required during start up for Anaerobic Contact Process and UASB

		Anaerobic Contact- gas phase	**Anaerobic Contact- acid phase**	**1 unit UASB**
	Unit	**Value**	**Value**	**Value**
Heat from the fluid required				
Volume tank	m^3	5942	1526	636
mass of liquid inside tank	kg	3,666,845	911,614	413,280
Total surface area, A	m^2	2140.93	848.21	692.68
Density of mild steel	kg/m^3	8030	8030	8030
C_p liquid	KJ/kg °C	4.2	4.2	4.2
Δ T	Celsius	15	15	15
Heat Transfer coefficient. From tank/air	W/m^2 °C	0.91	0.91	0.91
Heating time	second	36000	36000	36000
Wind factor (1 m/s)		1.4	1.4	1.4
Transfer rate coefficient, U1	W/m^2 °C	1.274	1.274	1.274
Q_m liquid	kW	6417	1595	723
Heating the tank material				
Volume of the steel	m^3	40.68	14.42	13.85
Mass of steel	kg	326642	115788	111244
C_p steel	KJ/Kg °C	0.5	0.5	0.5
Q_m tank	kW	68	24	23
Heat losses from tank				
Ambient temperature	Celsius	20	20	20
Operational temperature	Celsius	35	35	35
T_m	Celsius	27.5	27.5	27.5
$\Delta T_m = T_m - T_{amb}$	Celsius	7.5	7.5	7.5
Q_m(sides+ top)	kW	20	8	7
Total mean heat transfer requirment				
$Q_{startup} = Q_m$ liq + Q_m tank + Q_m side	kW	6505	1628	753

Note: 1 kilo Watt = 1 kilo Joule/second

Most of the heat required in startup operation originate from the heat required to heat up the liquid. The heat required to heat up the reactor during start-up is greater for Anaerobic Contact than for UASB, due to its volume of liquid inside. Wind flow rate outside the tank is considered to affect the loss of heat during the heating process. Wind velocity of 1 m /s is used for the calculation, which means the digester tank are sheltered by some wall to prevent strong wind to contact the digester wall tank directly.

Heat transfer required for maintaining operational temperature is less than the heat transfer required for startup operation due to the heat requirement to heat up the liquid from initial temperature are no longer calculated (Table 4-6). In this case, heat is maintained by putting heated metal bar into the reactor for time to heat up the liquid within the reactor.

Table 4-6 Rate of heat loss calculation during operation in Anaerobic Contact Process and UASB

	Unit	Anaerobic Contact gas Value	Anaerobic Contact acid Value	1 unit UASB Value
Heat from incoming liquid				
Mass of liquid	Kg/s	1.77	1.77	0.46
C_p liquid	KJ/kg °C	4.2	4.2	4.2
Δ T	Celsius	0	15	15
Qm liquid	kW	0	112	29
Heat loss from solid surface to atmosphere				
Operational temperature	Celsius	35	35	35
Ambient temperature	Celsius	20	20	20
T_m	Celsius	27.5	27.5	27.5
ΔT	Celsius	7.5	7.5	7.5
Q_m side	kW	20	8	4
total mean heat transfer requirements				
Qoperation = Qm sides + Qm liquid	kW	20	120	33

Note: 1 kilo Watt = 1 kilo Joule/second

The UASB heat rate listed in Table 4-6 were calculated for one reactor, while total heat rate required to maintain the working temperature is the calculated heat rate times the unit number. After maintaining the heat during startup, the energy requirement for maintaining heat loss during operation for Anaerobic Contact and UASB is 140 kW (Acid phase and Gas phase) for Anaerobic Contact and 33 kW for 1 unit of UASB. Total energy consumption of UASB during operation is 132 kW (from 4 units of UASB reactor).

4.4 Process Flow Diagram

Based on the data acquired from calculation and design parameter used to treat the type of wastewater, a process flow diagram was built and presented in Figure 4-1. Three feed tanks contain wastewater and optional water prepared. The water tank is used to store water for diluting the concentration of the wastewater COD by mixing it. The water is used if wastewater contains greater COD than the recommended average COD inlet concentration designed in this calculation. Grit removal is used to remove debris which may be in the raw wastewater. DAF unit is presented to remove particulate COD before entering the digester tank. Equalization tank used to control the flowrate coming to the digester. Recirculation of sludge is maintained by membrane unit outside the digester. The gas produced from the anaerobic digestion is stored partially in the digester tank, and the rest is stored in the balloon container. Effluent water from the digester is treated by aeration to reach an allowable COD and BOD concentrations to discharge into the water body of sea or lake.

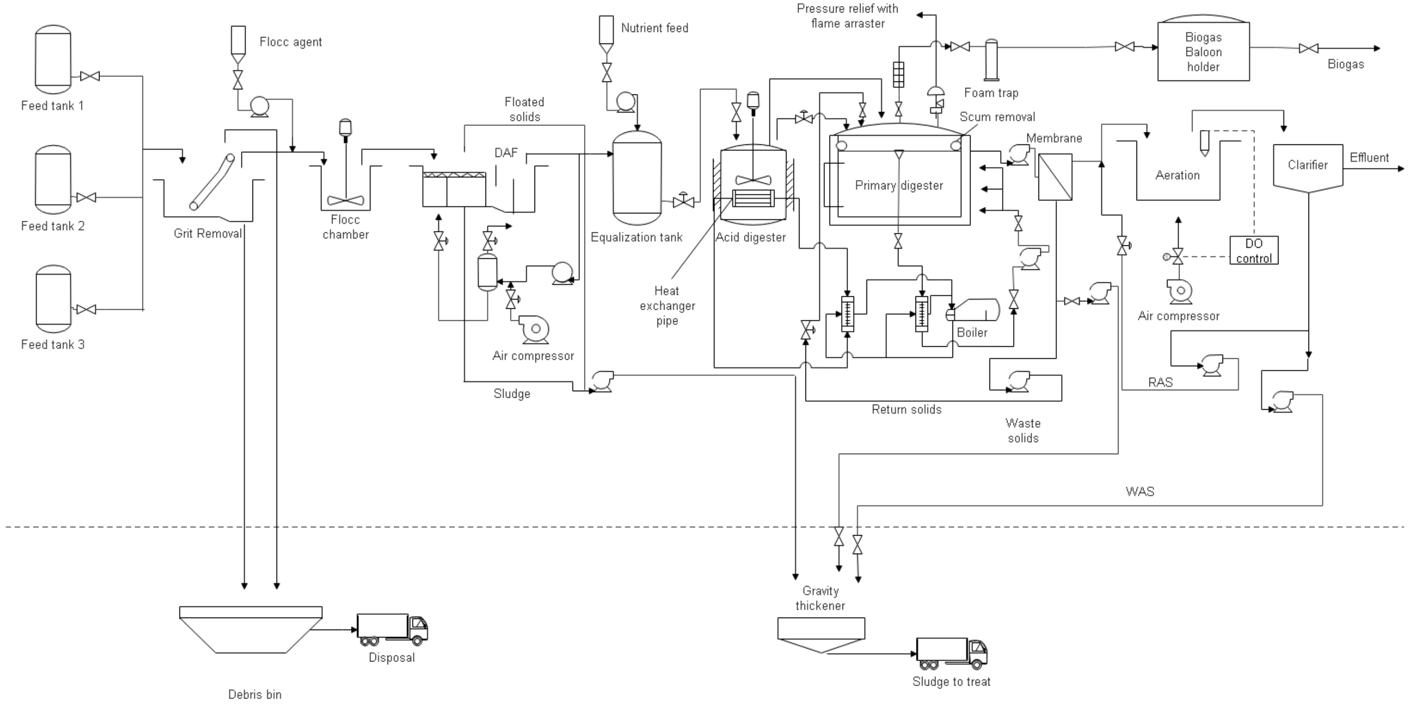

Figure 4-1 Process flow diagram for treating glycol based waste using Anaerobic Contact Phase

4.5 Bio-Potential Test of Wastewater Samples

This part of the chapter contains the results of test investigating bio-degradability of the collected samples. Bio-potential test and wastewater characterization data are the main focus of this part.

4.5.1 Ion Concentration Measurement

The ion concentration in the wastewater samples was measured by ion chromatography. Four samples containing Slop water A, Slop water B, contaminated MEG, and used coolants, were prepared and tested. Slop water contains a mix of the chemical from the rig's drainage. Two different sample of Slop water with unknown source and composition collected. After calculating the peak area in the chromatogram, the concentrations of the samples were determined using reference water as standard water with known concentration.

Table 4-7 shows ion concentrations (Ci) in each sample.

Slop water A contains such ions as sodium, magnesium and calcium, which may affect the efficiency of the methane bio-production. Slop water B has ion concentration of calcium and sulfate in the range that may strongly inhibit the process of degradation, 5820.3 mg /l, and 6225.39 mg /l, respectively. Contaminated MEG and used coolants samples contain low concentration of ions and are categorized as safe from inhibition process by ion concentration.

Table 4-7 Ion content dissolved of the samples

	Sodium ion Ci (mg /l)	Potassium ion Ci (mg /l)	Magnesium ion Ci (mg /l)	Calcium ion Ci (mg /l)	SO4 (as H2S) Ci (mg /l)
Slop water A	2551.30	62.49	199.59	294.57	37.40
Slop water B	3400.87	1966.57	18.94	5820.30	6225.39
Contaminated MEG	22.54	9.60	0.00	24.44	<0
Used Coolants	319.13	148.65	0.86	3.81	22.24

Table 4-8 shows the effect of these ionic concentrations on the biodegradation process. The conditions are divided into four categories; fairly, stimulatory, moderately inhibit, and strongly inhibit the process of biodegradation.

Table 4-8 Ion effect on inhibition of biodegradation process

	Sodium ion	Potassium ion	Magnesium ion	Calcium ion	SO4 (as H2S)

	Effect	Effect	Effect	Effect	Effect
Slop water A	moderate	Stimulatory	moderate	moderate	fair
Slop water B	moderate	moderate	fair	Strongly	strongly
Contaminated MEG	fair	fair	fair	fair	fair
Used Coolants	stimulatory	stimulatory	fair	fair	fair

4.5.2 COD Measurement

The tests were conducted to picture the COD concentration in industrial wastewater, which will be treated in the wastewater treatment plant. The total COD value of the collected samples varied from low to very high (Table 4-9). The filtered COD indicates that the soluble COD presents in the samples. The fraction of soluble COD in MEG, used coolant and Slop water A are 0.99, 0.97, and 0.96, respectively. pH of the contaminated MEG was tested and appeared to be in the range of base, while the other samples were slight off from neutral pH.

Table 4-9 COD measurement and pH of wastewater samples

	Total COD (gr/l)	Filtered COD (gr/l)	pH
MEG	146.1	144.4	9.38
used coolant	59.2	57.4	7.57
Slop water A	1.125	1.08	6.64
Inoculum	1.235	NA	6.8

4.5.3 Biogas Potential Batch Test

Ten samples were prepared and tested during 14 days of operation. The results were recorded automatically by the AMPTS II software. The accumulated methane gas volume produced during the trial is presented in Figure 4-2, and the average data of the samples is presented in Figure 4-3.

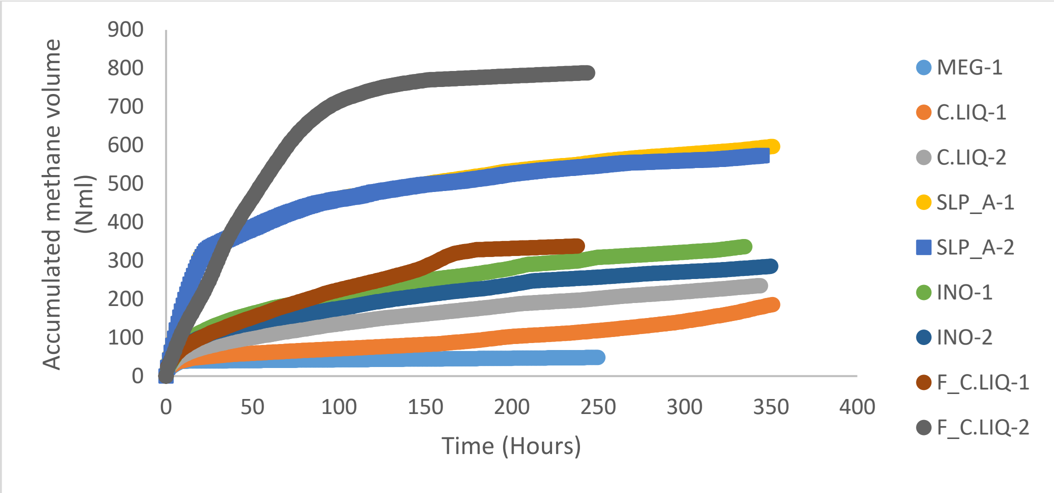

Figure 4-2 Accumulated methane gas volume produce against time in hours

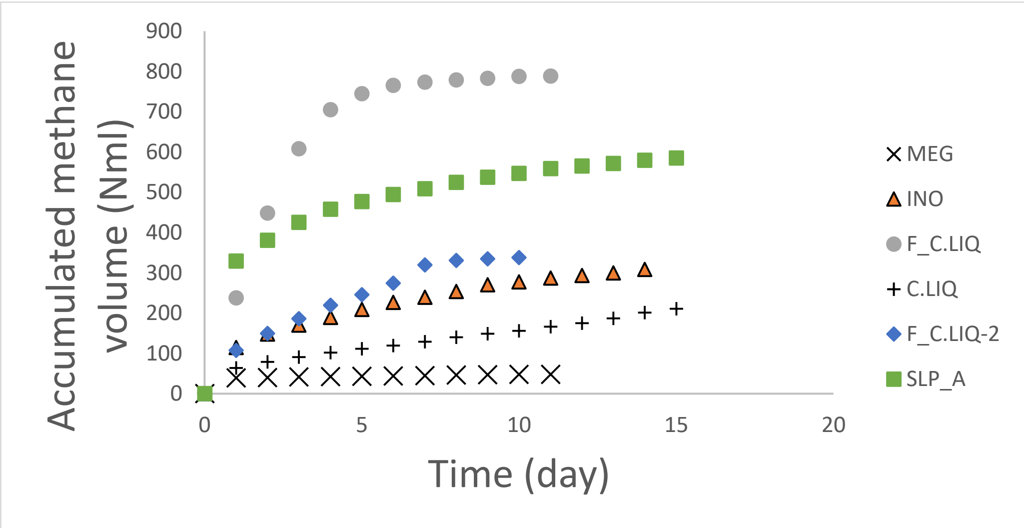

Figure 4-3 Average accumulated methane gas volume produce against time in days

The results are not meant to be used directly into design parameter calculation because the settings in this experiment were not standardized to the proper step to calculate the potential biogas value. The test was meant to verify the inhibition process caused by bio-pesticide chemicals, which might be inside of used coolant sample. Performances of contaminated MEG and used coolants samples were under the level of inoculum sample that acts as the blank to measure the methane produced from the original sample (Figure 4-3). The batch bottle, which contains 50 ml of filtered coolant, has the highest amount of gas produced in the test (732.1 ml), while contaminated MEG with 100 ml of sample was the lowest with value of 43 ml. The summarized data from bio-potential test is presented in Table 4-10. The % of COD removal and methane yield are not calculated in this study due to performance failure of the batch test because of massive COD input to the system which exceeded the typical COD load to the batch reactor.

Table 4-10 Volume of gas produced from batch test

Sample name	COD load into batch reactor (g/l)	Volume of methane produced (Nml)
Filtered C. liquid + Inoculum	57.4	732.1 ±56.3
Slop A + Inoculum	1.125	579.6 ± 9.8
MEG + Inoculum	146.1	43 ± 5
Coolant + Inoculum	59.2	201.6 ± 30.6
Inoculum	1.23	280.7 ± 27.8

4.6 Estimated Capital Cost

The cost of materials used for building the frame of UASB and Anaerobic Contact was calculated based on the material construction requirement.

4.6.1 Materials and Cost of Digester Construction

Two options were used to choose the construction material for the digester wall. The first option was to use stainless steel metal and the second one was to use concrete cement. Stainless steel grade EN 1.4301/AISI 304 is used for part of digester, which is in contact with liquid, while EN 1.4571/AISI 316Ti is used for gas chamber part. Table 4-11 lists all required materials to construct the digester body. The amount of stainless steel metal needed to build was calculated based on the thickness of stainless steel used in each type of digester.

Table 4-11 List of materials for digester construction

		Gas phase tank	Acid phase tank	1 unit of UASB
	unit	quantity		
Concrete				
Rebar #6	MT	215.5	35	55.2
Cement	ton	875	142.3	224
Sand	m^3	1078	175	276
Gravel	m^3	2155	350	552
Metal				
Steel 304	ton	154	22	83.9
Steel 316	ton	89.5		36.7

A ratio of 0.53 l/kg water per cement, and cement:sand:gravel:mass ratio of 1:2.2:3.7 were used as a basic concrete mixture for floors, driveways, structural beams, and columns [29]. Reinforced bars, used for the construction, are 6Ø6 m^{-1} or 6Ø8 m^{-1} (NØD m^{-1}, where N is the number of iron rods per meter length, and D is the diameter of iron rods). Rule of thumb was used to calculate the amount of iron bar needed. 80 kg of rebar was used in one cubic meter of the concrete slab. The other rule of thumb which can be used to calculate iron bar necessity is 1 % of concrete's volume is converted into volume of iron bar required.

The total cost estimations of the reactor constructions were done based on data on BRØDRENE DAHL website, MICRODYN NADIR membrane catalogue and Vi-Tek concrete reactor quotation price. The bio-reactor estimation cost was calculated based on the quotation price of 1088 m^3 reactor by Vi-Tek. The price include the cost of concrete material, reactor mixing system and thermal isolator.

Table 4-12 shows the estimated price for the digester material construction.

Table 4-12 Estimated price list for bio-reactor construction

Material	Unit	Price
Bioreactor	NOK/m^3	1,838.24
6" SS pipe 316	NOK/m	510.00
Motor	NOK/kW	5845.00
MBR filter	NOK/unit	2,128,500

The estimated cost for building Anaerobic Contact digester is the sum of cost of Anaerobic Contact acid phase tank and Anaerobic Contact gas phase tank. While UASB construction is calculated for four tanks of UASB required to treat the wastewater. Table 4-13 compares the estimated construction cost of Anaerobic Contact reactor with UASB using concrete as its frame material.

Table 4-13 Estimated construction cost of digester

		Estimated Price	
Material	Unit	Anaerobic Contact	UASB
Concrete	NOK	16,254,028.90	6,976,035.00

4.6.2 Piping and Motor Pump

The amount of pipes estimated in this calculation is based on rough estimation from PFD diagram. 6″ pipe or 8″ pipes can be used as a connector from the digester. The diameter should maintain a minimum velocity five fps in order to avoid settling of solid in the piping, and an internal diameter of pipe should remain constant, so the velocity will not change. The digester reactor is connected by pipe line to the external recirculation pump and is connected back to the inlet stream pipe of the digester. A PVC with pipe pressure of 200 psi is recommended for this application. Roughly around 93 meters and 161 meters of the 6″ pipe are required for the digester connection of Anaerobic Contact and UASB, respectively (see Figure 4-4).

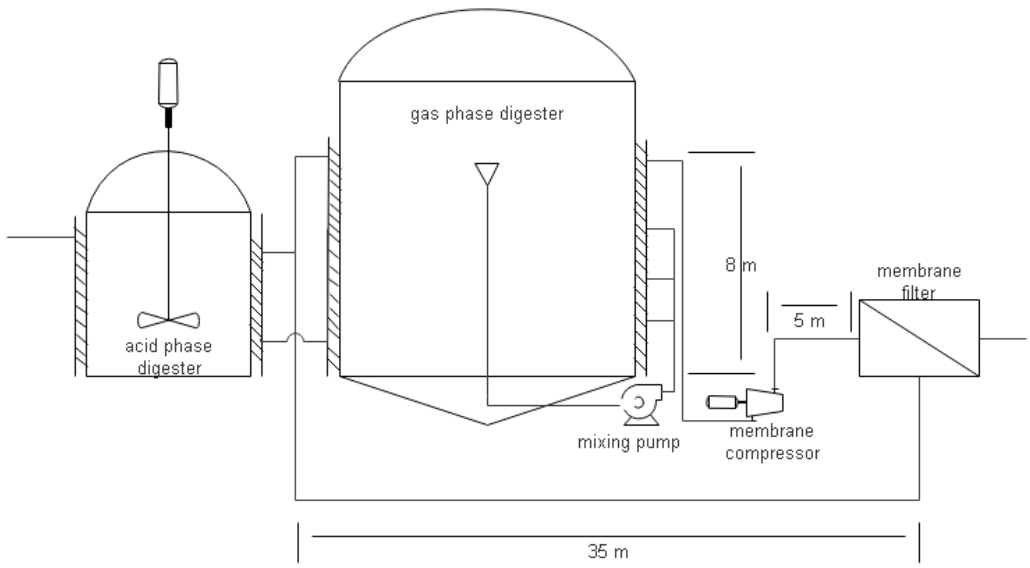

Figure 4-4 Liquid pipeline of Anaerobic Contact reactor

The gas system must have resistivity to corrosion due to H_2S production from the degradation process. Commonly, low copper cast aluminum materials are used to handle biogas system. Stainless steel pipe is excellent choice for the gas piping system. It has corrosion resistance and excellent formability. EN 1.4404/AISI 316L material pipe is the type that recommended to use. The protective coating is recommended to prevent corrosion if fabricated steel used. Epoxy coating and bitumastic coating are recommended to coat the material.

Choice of pipe diameter, length, and fitting is based on The Water Environment Federation (WEF Manual of Practice No.FD – 8), where pipe should be sized with maximum gas velocity below 12 ft/s (3.7 m/s). To reduce pressure loss the number of pipe bends should be minimized.

The pumps used in the biogas plant may be diesel pump or electric pump. Electric pump may give more efficiency compared to the diesel pump. Centrifugal pump is chosen as the feed pump into the digester which provides low torque requirement and less susceptible to plugging. It is capable of handling wastewater with total solids up to 10%. Return pumps will have more solids to handle compared to the feed pump. A sludge thickener based on microfiltration membrane filter will be used to treat effluent of the digester and return the sludge into digester system.

Mixing system selected for the digester is the mechanical pumping system. Three options are available for mechanical pumping system. As it is shown in the PFD picture (Figure 4-1), external recirculation pump was selected. The other two types of mechanical pumping system are shown in Figure 4-5. The unit powered by the motor is estimated based on the volume of the digester with ratio 0.005-0.008 kW/m^3 of digester volume[22]. 10 kW motor is used for acid phase tank and 50 kW motor for gas phase tank in Anaerobic Contact. For UASB reactor, 15 kW motor is selected.

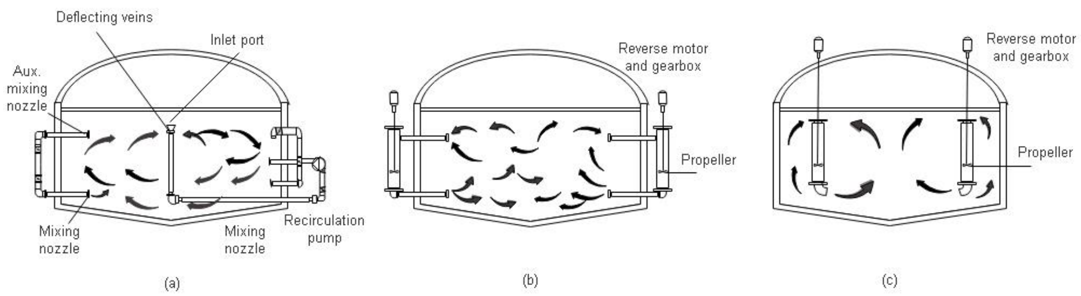

Figure 4-5 Mechanical pumping system: (a) external pumped recirculation, (b) external draft tube, (c) internal draft tube

5 Discussions

This chapter discusses the results from bio-potential tests conducted and explicates the connections to biodegradation process, the decisions made for selecting the design parameters and unit installed in the recommended anaerobic digester system. Lastly, Anaerobic Contact and UASB design parameters are compared to each other, while the merits and demerits of the systems are evaluated.

5.1 Bio-Potential Test

The objective of the experiments conducted in this study is to get the complete picture of the industrial wastewater characteristics and to suggest a suitable design of the bio-reactor for treatment of industrial wastewater. This industrial wastewater consists of mixture of the chemicals. Depending on the type of the industry, the wastewater characteristics may vary. For this project, wastewater, which will be treated, is the waste that consists of glycol and organic acid. Many studies show biodegradation for both of the chemicals (glycol and organic acid) in biomass under aerobic and anaerobic condition [14-17]. Wastewater coming from the car industry, including coolant, are the main subject of the design. The coolant composition might have bio-pesticide that will affect the degradation process of the waste. To ascertain this assumption, the bio-potential test was conducted. The other reason to conduct this experiment was to analyze the salinity of the wastewater from the oil and gas industry. Slop water usually has an uncertain composition on it. All the water, collected from the drainage at the rig, placed in the same container and send offshore to treat. The slop water usually contains sea water which has salinity content and might decrease the kinetic of biodegradation.

Table 4-10 lists the values of bio-methane produced during the test. Inoculum acts as the blank concentration for the test, which contains a substrate and heterotrophic bacteria. The volume of the biogas produced from the samples was subtracted from the gas produced by the inoculum sample. This condition applied if the batch reactor test runs with high efficiency. The results shown in Table 4-10 indicate that reactor is not functioning properly for MEG sample and used coolant sample. The performance from both of the samples was lower than the inoculum sample. The MEG sample produces only 43 ml of biogas compared to the inoculum, which produces 280.7 ml of biogas.

According to the pH test and COD test of the samples listed in Table 4-9, the pH of MEG is in the base range, while the COD load in the reactor is high using ratio 2:3 to the inoculum. The same case occurred to the used coolant sample; the COD load exceeded the standard COD load in a batch reactor, a total of 59.2 gCOD placed into the 250 ml reactor. Acideogenesis is the reaction with highest kinetic coefficient compared to other steps in anaerobic biodegradation. 0.1-0.2 gVSS/gCOD of yield was achieved in this step. The products from acidogenesis are mainly short-chain fatty acids (SCFA) and hydrogen. The pH of the reactor might be decreased and there is a possibility of accumulation of FVA in the reactor, which is toxic to the methanogens bacteria. When all alkalinity is consumed by the produced acid in the carcinogenesis reaction, the pH starts to drop, which leads to inhibition of the methanogenesis steps. The parameter that should be maintained is the pH in the reactor. This experiment should be run with the addition of buffer to increase alkalinity and maintain the pH during the acidogenic steps.

Filtered coolant sample, tested using ratio 1:3:1 for Sample:inoculum:water, performed better than the coolant sample. But the amount of COD converted into biogas is still low. With 65 % COD removal efficiency, the methane produced from the filtered coolant estimated to be 3.2 liters and inoculum sample would produce 0.3 liter.

Ion concentration of the wastewater might inhibit the process at a certain level. Ion chromatography instrument is the suitable method to measure the ion content dissolved in the wastewater sample. From Table 4-7 and Table 4-8, there is an indication of strong inhibition in anaerobic biodegradation from Slop water B sample, which might occur if bio-potential test were conducted. The strongest effect is coming from sulfate (as H_2S) with a concentration of 6225.39 mg /liter, while the threshold level of sulfide is 200 mg/ liter. Hydrogen sulfide is partially soluble in water. In water, it releases hydrogen ion, what will decrease the pH. Slop B sample is not suitable for biogas anaerobic treatment because it will strongly inhibit the process by reducing the yield, and H_2S in gaseous form is corrosive to the system. Test for used coolant sample surprisingly showed a reasonable concentration of ions which may indicate the potential to be treated by anaerobic degradation.

This experiment alone cannot confirm the basic assumption bio-pesticide presence in the coolant. The biogas production increased when the COD load to the reactor was adjusted to lower level. A proper test in bio-potential is required to measure thoroughly the COD removal efficiency of coolant wastewater sample.

5.2 Pre-Treatment of Inlet Water

Anaerobic treatment reactor was selected to treat the sample with a predetermined parameter of the concentration of COD_{solube} 70 kg /m^3 and 5000 m^3 of waste per year. Other than the COD, flowrate, probability to contain high salinity, and presence of glycol, there is no other data available as an input. The composition of wastewater sample is not available when the writer does the calculation on the design. The important parameter, which is usually considered for the reactor design, is the COD fraction of the wastewater; soluble COD, particulate COD also the ratio of degradable COD in it.

Three feed tanks with an average volume of 500 m^3 were prepared to hold the waste transported to the site. One tank is prepared to contain water if the industrial wastewater has exceeded COD and salinity level set for the design. Screen or grit removal is placed after the feed tank to remove debris from wastewater.

The design calculation is intended to treat soluble COD from the wastewater, not the sludge. Hence a pre-treatment unit is used to remove the particulate COD. The instrument selected is the DAF (dissolved air flotation) unit. This unit is available in the company, and it can be utilized to treat the waste. The DAF unit contains a flocculation chamber, which is used to mix wastewater with flocculants agent and stirred gently. The flocculent agent is added into the mainstream pipeline to increase contact time and get mixed with the wastewater inlet. DAF with circulation unit is selected and it will pressurize the recycle flow and mix it with influent before entering the flocculation chamber.

The equalization tank is selected to control the inlet flow into the digester. 300 m^3 tank is prepared to hold the inlet water. The size is calculated based on the estimated time detention of 2 days from inlet water with 150 m^3/day flowrate.

5.3 Anaerobic Contact and UASB

5.3.1 Anaerobic Contact Reactor Design

The SRT of Anaerobic Contact may vary from 15 to 30 days to achieve process stability and considering safety factor. In this case, the inlet wastewater contains very high COD, mostly soluble, because of the pre-treatment of DAF. The HRT in Anaerobic Contact process is set equal to SRT to provide the time needed for the thickening process of effluent solids. This concept is similar with the CSTR to treat high concentration of soluble COD.

The Two-phase anaerobic digestion system was selected to accommodate the inefficiency of single staged anaerobic digestion. From the four options available for the two-phase anaerobic digestion, acid-gas phase was selected. The other two-stage types use heat treatment to achieve thermophilic digestion condition (50 – 57 °C). Heat treatment is considered expensive, especially in large reactor. Thus, the heat treatment in this design is only used to maintain the mesophilic temperature (35 °C). The acid-gas phase splits the process into fermentation and methanogenesis. Hydrolysis step is neglected because the wastewater contains few solids. The acid phase, which runs in the first reactor, is operated at pH 6 or less and has less SRT compared to the gas phase. In the calculation, the SRT is set for three days in acid phase and 26 days in the gas phase. The gas phase is controlled to suit the condition of methanogenesis steps. With this type of process flow, the reaction can be maintained more easily compared to single stage phase.

The MVSS is the portion that digests the incoming substrate; it is a part of the total MLSS inside the digester. MVSS contains microorganisms and organic matter in the form of sludge. The calculation of MVSS in a different value of SRT is shown in Appendix 1: Table A- 2 and Table A- 3.

The amount of MVSS solids produced from the selected SRT thus is converted into the minimum volume of liquid required to digest the substrate. The higher SRT values is set for the design, the more volume of liquid is required. Typically a certain conversion factor is used to overcome the efficiency which is not hundred percent. An assumption of 80 % efficiency is commonly used. Thus the effective volume is multiplied by 1.25. Another multiplier commonly used is 1.2. It is used to consider the dead volume inside of the reactor.

In the Anaerobic contact reactor, the SRT is set at 29 days to maintain the solids longer inside of the reactor and achieve high efficiency of degradation. The value of efficiency rate in the calculation was set at 0.9. This efficiency is achievable when the parameters are maintained during operation. Consideration of adding nutrients is also taken in account, because the wastewater, which originally comes from industry, has less organic nitrogen and phosphorous compared to the municipal wastewater. The nutrients input process is started in the equalization tank, or it can be injected from the mainstream pipe that goes to the digester. One of the advantages of Anaerobic Contact reactor is its ability to withstand shock from wastewater inlet. The characteristic of industrial wastewater cannot be predicted and the COD and salinity may vary far from safety level of reactor design parameter. The large volume of the Anaerobic Contact reactor can dilute the incoming wastewater, reducing the shock effect.

The main body of the digester's material can be selected from metal or a concrete cement. The cost of building the tank from the concrete is more suitable for treating wastewater in large volume compared the metal tank. The price of the metal per cubic meter is considered more expensive especially when the material used in large volume. Certain thickness is calculated to withstand the working pressure of the digester. The main pressure comes from the solids contained in the MLSS. The more MLSS set for the digester, the more static pressure of the liquid is applied to the digester wall. The concrete body of reactor provides the good strength required to withstand the working pressure. Some part of the digester body is placed under the ground level. 2-3 meter of the body is placed to stabilize the concrete building. Insulation of the wall is an important aspect of building the digester. Lining process is implied by mortar or using insulator foam to cover side body of reactor that contact with air. The loss of heat to the air is a problem of the digestion process while maintaining the temperature is also costly. The heat loss due to heat transfer to the contact with wind is categorized as a significant factor. A reactor that directly exposed to the wind with velocity of 6 m/s suffered from multiplication factor of 3.0 for the heat loss calculation. The heat loss calculations in this study are based on the carbon-metal as the frame of the digester.

The heat of the reactor body is maintained by heat transfer unit from the boiler. The most effective ways to heat the system is by using in site heating system. The body of the digester is surrounded by the heat pipe, which transfers the heat coming from hot water inside the pipe through the liquid body of the digester. A stainless steel corrugated pipe system is the best option available for in site heat blanket system. Other pipe materials used for heat blanket are carbon steel and polyethylene, but they lack heat transfer ability compared to the stainless steel, thus the installation inside requires more line compared to stainless steel. Standard 2″ of the pipe is used for the installation. 113 meter and 176 meters of the pipeline are required to install inside the acid phase digester and gas phase digesters.

The gas produced from the digester is collected in the roof part of the digester. Usually the frame of the gas holder inside of the tank is made of a light material such as wood with a net or stainless steel frame. The biogas holder itself can be placed inside or outside the digester. A membrane type holder used for this application.

5.3.2 UASB Design Comparison

Initially, UASB is designed to treat the effluent of the wastewater plant, which still contains organic matter exceeding the safely dischargeable COD level. It is used to treat soluble COD in the wastewater. The wastewater which contains protein and fats is not suitable for this type of reactor. The other aspect that needs to be concerned is the TSS concentration in the inlet. The recommended concentration of TSS is less than 6 g TSS/l. This concept is suitable with the industrial wastewater characteristic to contain glycol. The only drawback is the ratio of COD: N: P from the wastewater. To overcome the problems, the addition of nutrients into the reactor is necessity. The operational cost will vary, depending on the inlet concentration of N and P from the wastewater.

As it can be seen from Table 4-4, the UASB reactor unit is divided into four units, based on the recommendation of UASB reactor size efficiency. The UASB reactor volume is not supposed to exceed 500 m^3 per unit of the reactor. The reactor's minimum volume required set on 473 m^3/ unit of the reactor. With this setting, OLR set at 6.67 kgCOD/$m^3 \cdot$d, SRT at 50 days and HRT at 11 days. The HRT value is unusual to the typical design of UASB, mostly it range between 6 – 14 hours. Long HRT is related to a low up-flow liquid velocity, and it may facilitate the growth of dispersed bacteria and less favorable for granule formation. The value of HRT depends on the up-flow velocity and the temperature setting of the reactor. The up-flow velocity for wastewater which contains nearly 100% soluble COD set on 1.0 to 3 m/h, but if the wastewater contains high concentration of COD, the up-flow velocity is set based on the organic loading rate.

The calculated value of the up-flow velocity is 0.03 m /h. This is a measure based on the inlet COD concentration. With the reasonable up-flow velocity value of 0.5 m/h, the height of the reactor should be set at 241.7 m. This nominal height does not make sense.

Practically, the up-flow velocity of 0.03 m/h is very hard to achieve by the inlet valve of the reactor. The design parameter of the wastewater is exceeding the design limit of the UASB. To overcome the up-flow velocity problems, an external circulation system is used (see Figure 2-11). Internal circulation pump the liquid from the upper part of the reactor and injected to the bottom part of the sludge bed to increase the agitation and shear force up to the recommendation up-flow velocity.

The up-flow velocity is very crucial, and it became the principal of mixing system in the UASB digester. Mixing the sludge bed induces the shear force which helps the anaerobic granules become stable and increase the formation of the granules[30]. The up-flow velocity of the UASB calculated in this case of study is 0.03 m/h, which is not the minimum standard up-flow velocity recommended by Letingga in Table 2-1.

The disadvantage of this design is its capability to handle shock from high concentration of COD and salinity in wastewater. The UASB reactor volume is design to be minimalist, to overcome the cost of construction in conventional design. But in the case of shock condition, the reactor is less powerful compared to CSTR or Anaerobic Contact which has more volume than UASB. A high concentration of COD and salt in wastewater will change the UASB reactor environment (pH and Salinity), reducing the kinetic reaction by interfere the microorganisms activity.

5.4 Cost Analysis

The cost analysis is based on the amount of materials needed to build the digester. Concrete based material becomes the best option over stainless steel metal. Table 4-13 showed the estimated price to construct the digester. The UASB design requires less volume than Anaerobic Contact reactor but the unit of UASB was split by 4 units. The option to use stainless steel metal is considered expensive when the reactor built in large scale. This cost analysis is just rough estimation to build the digester. A thorough LCC analysis is required to get the picture of building the system.

Table 5-1 shows a rough estimation of cost elements that need to be considered for investing on digester unit. Need to be reminded, this cost is only calculated for the digester unit, not the whole anaerobic process.

Table 5-1 Capital cost of Anaerobic Contact Reactor

	Unit	UASB	Anaerobic Contact
Body + roof, agitator system	NOK	4,677,750.00	13,727,398.90
Heat system (boiler, circulator, heat panels)	NOK	288,000.00	288,000.00
Gas recirculating system (gas pump, diffuser, manifolds)	NOK	270,000.00	270,000.00
labor and supplies	NOK	373,500.00	425,500.00
Sludge centrifugal pump + connection pipe	NOK	169,785.00	398,130.00
Membrane System	NOK	2,128.500.00	2,128.500.00
Total	NOK	**7,907,535.00**	**17,237,528.90**

The pre-build reactor is available on the market, but the size selection is limited. Thus the constructing from scratch is preferable. The amount of material needed for concrete is following the certain ratio of concrete mix that has been tested in the past year[31]. Another mix ratio can be selected to reduce the construction cost, but the concrete need to have the strength to withstand static pressure from the liquid inside and it needs to be impenetrable by gas and water. B30 M60 type of concrete was selected by the construction company, this type commonly used for bio-reactor construction.

The costs of motor, compressor, and piping required for digester vary based on the location setup. A motor with 50 kW is required to run the mechanical mixing in the gas phase reactor and 10 kW in the acid phase reactor. A 6″ or 8″ HDPE pipe is recommended to use as connector to move slurry liquid.

Capital cost elements which need to be considered in investing on anaerobic bio-digester plant are: (a) Generation of equipment, (b) Balance of Plant (BOP), (c) Interconnection and (d) Reserves & financing cost. Generation equipment consists of all digester hardware purchasing costs. Balance of plant represents all infrastructure, site preparation and labor supporting the installation of the generation equipment. BOP costs include foundations, mounting devices, other hardware, and labor not already accounted for in the Generation Equipment.

The Interconnection should account for all project costs relating to connecting to the grid, such as the construction of transmission lines, permitting costs with the utility, and startup costs. The Development Costs should include all costs relating to project management, studies, engineering, permitting, contingencies, success fees, and other soft costs not accounted for elsewhere in the "Intermediate" cost breakdown. The "Reserves & Financing Costs" row accounts for all costs relating to financing, such as lender fees, closing costs, legal fees, interest during construction, due diligence costs and any other relevant finance related costs. This model was taken from Cost of Renewable Energy Spreadsheet Tool (CREST) by Sustainable Energy Advantage, LCC.

6 Conclusions

Bio-potential test of the samples collected from the *Norwegian Technology AS* was unable to determine the initial assumption made whether the used coolant liquid is containing bio-pesticide. The bio-potential test was conducted under unideal conditions of the anaerobic batch reactor thus the recorded biogas flow rate only explain the digestion run with reduced kinetic of an anaerobic chain of reaction. COD total concentrations of the tested samples are not adjusted to the limit of concentration level resulting the accumulation of SCFA in the final process. Total accumulation of methane gas from coolant sample is recorded to be 732.1 ml with pre-treatment condition using a filter to remove suspended solids. The lowest methane accumulation was recorded of the coolants sample when combined with inoculum sludge with a volume ratio of 2:3. Ion Chromatography test for the coolant sample showed light metal and sulpide concentrations at a safe level. Sodium and potassium ions concentrations have a slight stimulatory to the kinetic reaction of anaerobic digestion. Slop water B has the highest possibility of anaerobic reaction inhibition due to the high concentration of sulphide and calcium ion.

The more feasible option of anaerobic reactor type selected for this study is the Anaerobic Contact reactor. Original design of UASB is not feasible to treat the high concentrated COD wastewater due to limitation of the COD input. A modification of UASB with internal re-circulation can be selected to treat the high COD wastewater but in general UASB is not suitable with shock process caused by the high salinity of COD load. The Anaerobic Contact reactor is divided into two parts. The acid phase digester is 6 m in height and 18 in diameter. The gas phase digester dimensions are 9 m in height and 29 m in diameter. SRT is set at 29 days with total sludge production of both reactors at 1745 kg /day.

The total construction costs of acid phase and gas phase reactors were estimated at 17,237,528.90 Kr for construction made from concrete. The UASB reactor has less construction cost to build, but it becomes not feasible for the purpose to treat the wastewater with the pre-determined characteristic. The estimated cost of construction of UASB reactor is 7,907,535.00 Kr for concrete frame. The motor power suggested for mixing purpose was estimated at 15 kW and 50 kW of power to circulate the liquid inside the reactor using water pump, which is connected in a different level of reactor height to maximize the efficiency of the mechanical pumping system.

7 Suggestions

The bio-potential test should be run on the genuine industrial wastewater sample to ensure the parameters added to the biogas digester calculation are fit to the model of the reactor. Complete analysis of COD fractionation test is recommended to get ratio of un-biodegradable in the wastewater thus can be input to the design calculation. A small-scale pilot reactor can be made based on the computed data in the biogas design calculation. A CSTR pilot scale reactor is an excellent choice of the reactor to monitor the sludge production within the reactor. The test should be recorded at least 60 to 90 days to reach steady state condition of the reactor, and the organic volumetric load rate can be adjusted to reach a high efficiency of COD conversion into methane.

A complete installation details are required to obtain as P&ID diagram of the suggested design. Sand and grit removal can be removed from the process flow based on the quality of the wastewater. Modification of the heat control in digester can be done by selecting a different type of heat transfer method such as heat blanket inside the reactor. A corrugated stainless steel pipe is the best option to maintain the heat. As an alternative, a cheaper polyethylene pipe can be used to replace the stainless steel pipe, but the heat transfer efficiency is less than that of stainless steel. Another model of mixing process inside reactor can be selected to increase the efficiency of the process. Gas lifter or gas diffuser combined with mechanical agitator of blade were reported to have highest mixing efficiency[9].

A different model of the reactor in CSTR model can be used to compare against the anaerobic contact reactor to get a better comparison of design. Lastly, thorough cost analysis, based on the information from manufacturers, is recommended to get a complete picture of all the cost related factors.

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Appendix

Appendix 1: Anaerobic Contact acid and gas phase design calculation

Table A- 1 listed design parameter used for acid phase of Anaerobic Contact reactor calculation

Table A- 1 Design parameter and assumption for acid phase, Anaerobic Contact reactor.

Design parameter	Unit	Value
Operational Temperature	**Celsius**	**35**
Solid yield Y	gVSS /gCOD	0.1
f_d (fraction of decay)	gVSS cell /g VSS decay	0.15
maximum specific growth rate (μ_m)	gVSS /gVSS.d	0.35
Ks	mg /l	160
Decay coeff (K_d)	gVSS /gVSS.d	0.04
MLSS	g /m^3	4000
Flowrate	m^3 /d	150
Inlet Soluble COD	Kg /m^3	70
Reactor efficiency	%	90
Solid retention time (SRT)	day	3.0
MVSS	kg	2860.0
MTSS	kg	3575.0
Sludge produce (P_x)	kg/d	1192
Volume liquid required	m^3	893.7
Volume effective	m^3	1072.5
Diameter : height		20:5
Diameter	m	18
Additional height due to gas volume	m	1

height	m	6.0
Total reactor volume (acid phase)	m^3	1526.0
Design parameter	**Unit**	**Value**
Mechanical design <u>(if using Steel)</u>		
sludge density	kg/m^3	1020
Static Pressure (ps) = ρ. G. H	kPa	60.04
working pressure	kPa	202.64
Total Pressure at base = Ps+P	Kpa	262.7
Max allowable pressure (1.33 x Ptotal)	kPa	349.4
material		carbon steel
working stress of carbon steel	KN/m^2	94408
Joint Efficiency Ej		0.85
Internal radius ri	m	3.4
Allowed corrosion range	mm	2.0
wall thickness = P. ri/(Sej-0.6P)		0.015
total wall thickness	m	0.017
outside tank diameter	m	18.03
Mechanical pumping for mixing		
Unit power = 0.007 KW/m^3 of digester volume		
Pump power	KW	11

a) Sludge production (Px) calculated by: $P_X = MTSS \cdot SRT$
b) Volume effective calculated by: Min. volume required x 1.2 (conversion factor)
c) Wall thickness: Max allowable pressure x internal radius/ (Joint Efficiency x internal radius – 0.6 max pressure).

The data calculation for daily VSS production rate for the acid phase of Anaerobic Contact reactor is shown in Table A- 2

Table A- 2 Daily MTSS produced in the acid phase reactor and minimum volume reactor requirement

SRT	EFFLUENT SOLUBLE COD (C_eff)	MX_h biomass	MX_e Endogen residue	MVSS total	MTSS	Liquid volume
day	mg/l	gVSS	gVSS	gVSS	gTSS	m^3
1	-241.16	911784.28	27353.53	939137.81	1173922.26	293.48
2	-454.74	1761368.42	105682.11	1867050.53	2333813.16	583.45
3	-2560.00	2623821.43	236143.93	2859965.36	3574956.70	893.74

a) Effluent soluble COD, Mx_h biomass, Mx_e endogen residue calculated based on Equation 2-12, Equation 2-13, and Equation 2-14 respectively.
b) MVSS total calculated by sum up the Mx_h biomass and Mx_e endogen
c) Minimum liquid volume calculated by : $MLSS = X_{TSS} \cdot v = P_{XTSS} \cdot SRT$

Data for technical design in gas phase reactor calculated and shown in Table A- 3

Table A- 3 Technical design parameter, assumption and calculation data in acid phase, Anaerobic Contact.

Design parameter	Unit	Value
Operational Temperature	**Celsius**	**35**
Solid yield Y	gVSS /gCOD	0.04
f_d (fraction of decay)	gVSS cell /g VSS decay	0.15
maximum specific growth rate (μ_m)	gVSS /gVSS.d	0.35
K_s	mg /l	160
Decay coeff (K_d)	gVSS /gVSS.d	0.02
MLSS	g /m^3	4000
Flowrate	m^3 /d	150
Inlet Soluble COD	Kg /m^3	70
Reactor efficiency	%	90
Solid retention time (SRT)	day	26.0
Effluent COD Concentration	kg/m^3	0.032
MVSS	Kg	11503.8
MTSS	kg	14379.8
Sludge produce (P_x)	kg/d	553
Volume liquid required	m^3	3595
Volume effective	m^3	4314
Ratio Diameter : height		20:5
Diameter	m	29
height addition due to gas volume	m	1.4
height	m	7.3

Total height	m	9.0
Total digester volume Gas phase	m^3	5941.7
Design parameter	**Unit**	**Value**
Volume gas Holder inside digester tank (optional)		
Max gas produce per day	m^3/day	6354
Gas storage = 0.6* volume gas produce per day	m^3	3812
Height addition	m	1.4
Sludge recovery (estimated)		
HRT from digester	days	28.8
Xu	kg/m^3	12000.0
Qr= Qin x (1-HRT/SRT)/(Xu/X_{TSS})-1	m^3/day	67.04
R = Qr/Qi		0.45
Q waste		
Q_w= MxTSS/ (SRT. X_{TSS})	m^3/d	138.27
Q waste from clarifier		
Q_w= MxTSS/ (SRT. X_{TSS})	m^3/d	46.09
Mechanical design (if using Steel)		
sludge density	kg/m^3	1020
Static Pressure (ps) = ρ. G. H	kPa	90.06
working pressure	kPa	202.64
Total Pressure at base = Ps+P	Kpa	292.7
Max allowable pressure (1.33 x Ptotal)	kPa	389.3
material		carbon steel
working stress of carbon steel	KN/m^2	94408
Joint Efficiency Ej		0.85
Internal radius ri	m	3.4
Allowed corrosion range	mm	2.0

wall thickness = P. ri/(Sej-0.6P)		0.017
total wall thickness	m	0.019
outside tank diameter	m	29.04
Mechanical pumping for mixing		
Unit power = 0.007 KW/m^3 of digester volume		
Pump power	KW	42

a) Sludge production (Px) calculated by: $P_X = MTSS \cdot SRT$
b) Volume effective calculated by: Min. volume required x 1.2 (conversion factor)
c) Wall thickness: Max allowable pressure x internal radius/ (Joint Efficiency x internal radius – 0.6 max pressure).

The data calculation for daily VSS production rate for gas phase of Anaerobic Contact reactor is shown in Table A-4

Table A- 4 Daily MTSS produced in the gas phase reactor and minimum volume reactor requirement

SRT	EFFLUENT SOLUBLE COD (C_eff)	MX_h biomass	MX_e Endogen residue	MVSS total	MTSS	Liquid volume
day	mg/ l	gVSS	gVSS	gVSS	gTSS	m^3
1.0	-243.58	371877.79	11156.33	383034.12	478792.65	119.70
2.0	-489.41	732005.43	43920.33	775925.76	969907.19	242.48
3.0	-16960.00	1329011.32	119611.02	1448622.34	1810777.92	452.69
4.0	540.00	1389200.00	166704.00	1555904.00	1944880.00	486.22
5.0	270.77	1711535.66	256730.35	1968266.01	2460332.52	615.08
6.0	182.86	2019710.20	363547.84	2383258.04	2979072.55	744.77
7.0	139.24	2316435.84	486451.53	2802887.36	3503609.20	875.90
8.0	113.17	2602681.92	624643.66	3227325.58	4034156.97	1008.54
9.0	95.84	2879103.64	777357.98	3656461.62	4570577.03	1142.64
10.0	83.48	3146243.48	943873.04	4090116.52	5112645.65	1278.16
11.0	74.22	3404583.03	1123512.40	4528095.43	5660119.29	1415.03
12.0	67.03	3654561.81	1315642.25	4970204.07	6212755.08	1553.19
13.0	61.28	3896586.02	1519668.55	5416254.57	6770318.21	1692.58
14.0	56.57	4131033.56	1735034.10	5866067.66	7332584.58	1833.15
15.0	52.66	4358257.45	1961215.85	6319473.30	7899341.63	1974.84
16.0	49.35	4578588.28	2197722.37	6776310.65	8470388.31	2117.60
17.0	46.51	4792336.27	2444091.50	7236427.77	9045534.71	2261.38
18.0	44.05	4999793.00	2699888.22	7699681.22	9624601.52	2406.15
19.0	41.90	5201232.84	2964702.72	8165935.55	10207419.44	2551.85
20.0	40.00	5396914.29	3238148.57	8635062.86	10793828.57	2698.46

21.0	38.31	5587081.15	3519861.12	9106942.27	11383677.84	2845.92
22.0	36.81	5771963.58	3809495.96	9581459.54	11976824.42	2994.21
23.0	35.45	5951779.04	4106727.54	10058506.58	12573133.23	3143.28
24.0	34.22	6126733.20	4411247.90	10537981.10	13172476.38	3293.12
25.0	33.10	6297020.69	4722765.52	11019786.21	13774732.76	3443.68
26.0	32.08	6462825.89	5041004.19	11503830.08	14379787.59	3594.95
27.0	31.15	6624323.55	5365702.07	11990025.62	14987532.03	3746.88
28.0	30.29	6781679.46	5696610.75	12478290.21	15597862.76	3899.47
29.0	29.50	6935051.00	6033494.37	12968545.36	16210681.70	4052.67
30.0	28.76	7084587.64	6376128.88	13460716.52	16825895.65	4206.47
31.0	28.08	7230431.49	6724301.29	13954732.78	17443415.97	4360.85
32.0	27.45	7372717.71	7077809.00	14450526.70	18063158.38	4515.79
33.0	26.86	7511574.92	7436459.17	14948034.09	18685042.61	4671.26
34.0	26.30	7647125.64	7800068.15	15447193.78	19308992.23	4827.25
35.0	25.78	7779486.59	8168460.92	15947947.51	19934934.39	4983.73
36.0	25.29	7908769.08	8541470.61	16450239.69	20562799.62	5140.70
37.0	24.83	8035079.29	8918938.02	16954017.31	21192521.64	5298.13
38.0	24.40	8158518.58	9300711.18	17459229.75	21824037.19	5456.01
39.0	23.99	8279183.72	9686644.95	17965828.67	22457285.84	5614.32
40.0	23.61	8397167.21	10076600.66	18473767.87	23092209.84	5773.05
41.0	23.24	8512557.48	10470445.70	18983003.18	23728753.98	5932.19
42.0	22.89	8625439.10	10868053.26	19493492.36	24366865.45	6091.72
43.0	22.56	8735893.00	11269301.97	20005194.97	25006493.71	6251.62
44.0	22.25	8843996.68	11674075.61	20518072.29	25647590.36	6411.90
45.0	21.95	8949824.36	12082262.88	21032087.24	26290109.05	6572.53
46.0	21.66	9053447.18	12493757.11	21547204.29	26934005.36	6733.50
47.0	21.39	9154933.34	12908456.01	22063389.34	27579236.68	6894.81

48.0	21.13	9254348.25	13326261.48	22580609.73	28225762.16	7056.44
49.0	20.88	9351754.68	13747079.38	23098834.07	28873542.58	7218.39
50.0	20.65	9447212.90	14170819.35	23618032.26	29522540.32	7380.64

a) Effluent soluble COD, Mx_h biomass, Mx_e endogen residue calculated based on Equation 2-12, Equation 2-13, and Equation 2-14 respectively.
b) MVSS total calculated by sum up the Mx_h biomass and Mx_e endogen
c) Minimum liquid volume calculated by : $MLSS = X_{TSS} \cdot v = P_{XTSS} \cdot SRT$

Combined data of Anaerobic Contact design calculation result presented in Table A- 5

Table A- 5 Complete Anaerobic Contact design parameter data

Design parameter	**Unit**	**Value**
Operational Temperature	**Celsius**	**35**
Flowrate	m^3 /d	150
Inlet Soluble COD	Kg /m^3	70
Total data of Acid Phase and Gas Phase		
Solid retention time (SRT)	day	29
MVSS	kg	14363.8
MTSS	kg	17954.7
Sludge produce (P_x)	kg/d	1745
Volume liquid required	m^3	4489
Total physical reactor volume(acid and gas phase)		7467.7
Methane Production rate		
COD degraded	KgCOD/m^3	69.97
Temperature	Celsius	30
CH4 yield = 0.4 l/g (273.15 +T)/(273.15+35)	l/gCOD	0.39
Methane production per day	m^3/day	4129.96
Total gas Produced per day (65 % methane)	m^3/day	6353.78
Energy Produce		
* energy density of methane at 30 °C	Kj/g	50.1
Methane density at 30 °C	g/L	0.635
Energy produce	Mj/day	131305.6
Nutrient Requirements		
Biomass produce	kg/d	1744.72
For N=12% of VSS		0.12

For P=2.4 % of VSS		0.024
N required	kg/d	178.0
P required	kg/d	35.6
Alkalinity req		
Operational Temperature	Celsius	35
CO2 phase	%	35
Calcium Carbonat needed	mg/L as CaCO3	2100
calcium carbonate in the influent **(assumption)**	mg/L as CaCO3	1300
calcium carbonate req = CaCO3 needed- CaCO3 inf	mg/L as CaCO3	800
Daily addition:	Kg/d as CaCO3	120
Clarifier dimension		
settling rate	m/d	24
Area	m^2	6.25
diameter	m	3
height	m	2.2
Total Height including sludge base	m	3.2

a) Total SRT calculated by: $SRT_{total} = SRT_{Acid\ phase} + SRT_{Gas\ phase}$
b) Total sludge production calculated by: $P_{x\ total} = P_{x\ acid} + P_{x\ gas}$
c) Recovery flowrate (Q_r) calculated by: $Q_r = Qin\ \frac{1-(HRT/SRT)}{(Xu/XTSS)-1}$
d) Waste flowrate (Q_w) calculated by: $Q_w = \frac{M_{XTSS}}{SRT \cdot XTSS}$
e) Daily Methane production: $Methane\ production = COD_{degraded} \cdot Methane\ yield$

Appendix 2: UASB parameter design

Table A- 6 listed design parameter used for UASB design calculation

Table A- 6 Design parameter and assumption for UASB acid phase

Design parameter	Unit	Value
Temperature	Celsius	35
Solids Yield, (Y)	gVSS /gCOD	0.08
f_d (fraction of decay)	gVSS cell /g VSS decay	0.15
maximum specific growth rate (μ_m)	gVSS /gVSS.d	0.35
Ks	mg /l	160
Decay coeff (K_d)	gVSS /gVSS.d	0.03
MLSS	g /m^3	30000
Flowrate	m^3 /d	150
Typical height UASB reactor	m	8
Inlet Soluble COD	Kg /m^3	70
Wastewater type		COD nearly 100% soluble
Up-flow Velocity	m /h	1.5
Reactor efficiency		0.9

Solid retention time (SRT)	day	50.0
MVSS	Kg	37785.6
MTSS	kg	47232.0
Sludge produce (P_x)	kg /d	945
Volume liquid required	m^3	1574
Volume effective	m^3	1890

Effluent COD Concentration	kg /m^3	0.027
Reactor per unit		
Unit of tank	pcs	4.00
Volume effective each tank	m^3	473
Dimension		
Area of reactor	m^2	59
Diameter	m	9.0
height addition due to gas volume	m	2.0
Total height	m	10.0
Volume reactor/ unit reactor	m^3	636.2
Volume all unit reactor	m^3	2544.7
Up-flow velocity	m /h	0.03

a) Sludge production (P_x) calculated by: $P_X = MTSS \cdot SRT$
b) Volume effective calculated by: Min. volume required x 1.2 (conversion factor)
c) Up-flow velocity calculated by: $v = \frac{Q}{A}$

The data calculation for daily VSS production rate UASB reactor is shown in Table A- 7

Table A- 7 Daily MTSS produced in UASB reactor and minimum volume reactor requirement

SRT	EFFLUENT SOLUBLE COD (C_eff)	MX_h biomass	MX_e Endogen residue	MVSS total	MTSS	Liquid volume
day	mg/l	gVSS	gVSS	gVSS	gTSS	m3
1.0	-242.35	736521.76	22095.65	758617.41	948271.76	31.61
2.0	-471.11	1436015.09	86160.91	1522176.00	1902720.00	63.42
3.0	-4360.00	2210333.94	198930.06	2409264.00	3011580.00	100.39
4.0	640.00	2675314.29	321037.71	2996352.00	3745440.00	124.85
5.0	306.67	3272556.52	490883.48	3763440.00	4704300.00	156.81
6.0	205.22	3832798.23	689903.68	4522701.91	5653377.39	188.45
7.0	156.13	4363798.88	916397.76	5280196.65	6600245.81	220.01
8.0	127.18	4868557.82	1168453.88	6037011.69	7546264.62	251.54
9.0	108.09	5349207.97	1444286.15	6793494.13	8491867.66	283.06
10.0	94.55	5807530.07	1742259.02	7549789.09	9437236.36	314.57
11.0	84.44	6245088.72	2060879.28	8305968.00	10382460.00	346.08
12.0	76.62	6663286.83	2398783.26	9062070.08	11327587.61	377.59
13.0	70.38	7063394.74	2754723.95	9818118.68	12272648.35	409.09
14.0	65.29	7446569.40	3127559.15	10574128.55	13217660.69	440.59
15.0	61.05	7813868.60	3516240.87	11330109.47	14162636.84	472.09
16.0	57.48	8166262.29	3919805.90	12086068.19	15107585.24	503.59
17.0	54.41	8504642.06	4337367.45	12842009.51	16052511.89	535.08
18.0	51.76	8829829.18	4768107.76	13597936.94	16997421.18	566.58
19.0	49.45	9142581.59	5211271.51	14353853.10	17942316.38	598.08
20.0	47.41	9443600.00	5666160.00	15109760.00	18887200.00	629.57
21.0	45.59	9733533.24	6132125.94	15865659.19	19832073.99	661.07

22.0	43.97	10012983.07	6608568.83	16621551.89	20776939.87	692.56
23.0	42.52	10282508.34	7094930.75	17377439.09	21721798.87	724.06
24.0	41.20	10542628.83	7590692.75	18133321.58	22666651.98	755.56
25.0	40.00	10793828.57	8095371.43	18889200.00	23611500.00	787.05
26.0	38.91	11036558.92	8608515.96	19645074.89	24556343.61	818.54
27.0	37.91	11271241.26	9129705.42	20400946.68	25501183.35	850.04
28.0	36.98	11498269.43	9658546.32	21156815.76	26446019.70	881.53
29.0	36.14	11718012.00	10194670.44	21912682.43	27390853.04	913.03
30.0	35.35	11930814.20	10737732.78	22668546.98	28335683.72	944.52
31.0	34.62	12136999.80	11287409.81	23424409.61	29280512.02	976.02
32.0	33.94	12336872.73	11843397.82	24180270.55	30225338.18	1007.51
33.0	33.31	12530718.56	12405411.38	24936129.94	31170162.43	1039.01
34.0	32.71	12718805.92	12973182.03	25691987.95	32114984.94	1070.50
35.0	32.16	12901387.66	13546457.04	26447844.71	33059805.88	1101.99
36.0	31.63	13078702.08	14124998.24	27203700.32	34004625.40	1133.49
37.0	31.14	13250973.88	14708581.01	27959554.89	34949443.62	1164.98
38.0	30.68	13418415.19	15296993.32	28715408.52	35894260.65	1196.48
39.0	30.24	13581226.39	15890034.88	29471261.27	36839076.59	1227.97
40.0	29.83	13739596.92	16487516.30	30227113.22	37783891.53	1259.46
41.0	29.44	13893706.02	17089258.41	30982964.44	38728705.54	1290.96
42.0	29.07	14043723.44	17695091.53	31738814.97	39673518.71	1322.45
43.0	28.71	14189809.99	18304854.89	32494664.88	40618331.10	1353.94
44.0	28.38	14332118.19	18918396.01	33250514.20	41563142.75	1385.44
45.0	28.06	14470792.76	19535570.23	34006362.99	42507953.73	1416.93
46.0	27.76	14605971.12	20156240.15	34762211.27	43452764.08	1448.43
47.0	27.46	14737783.85	20780275.23	35518059.08	44397573.85	1479.92

48.0	27.19	14866355.10	21407551.35	36273906.45	45342383.06	1511.41
49.0	26.92	14991803.00	22037950.41	37029753.42	46287191.77	1542.91
50.0	26.67	15114240.00	22671360.00	37785600.00	47232000.00	1574.40
51.0	26.42	15233773.21	23307673.01	38541446.22	48176807.78	1605.89
52.0	26.19	15350504.73	23946787.38	39297292.11	49121615.14	1637.39
53.0	25.96	15464531.92	24588605.76	40053137.68	50066422.11	1668.88
54.0	25.75	15575947.69	25233035.26	40808982.96	51011228.70	1700.37
55.0	25.54	15684840.74	25879987.22	41564827.95	51956034.94	1731.87
56.0	25.34	15791295.78	26529376.90	42320672.68	52900840.85	1763.36
57.0	25.15	15895393.79	27181123.37	43076517.16	53845646.45	1794.85
58.0	24.97	15997212.19	27835149.21	43832361.40	54790451.75	1826.35
59.0	24.79	16096825.06	28491380.36	44588205.42	55735256.78	1857.84
60.0	24.62	16194303.30	29149745.93	45344049.23	56680061.54	1889.34
61.0	24.45	16289714.78	29810178.05	46099892.84	57624866.05	1920.83
62.0	24.29	16383124.56	30472611.69	46855736.25	58569670.32	1952.32
63.0	24.13	16474594.98	31136984.51	47611579.49	59514474.36	1983.82
64.0	23.98	16564185.81	31803236.75	48367422.55	60459278.19	2015.31
65.0	23.84	16651954.39	32471311.06	49123265.45	61404081.82	2046.80
66.0	23.70	16737955.77	33141152.43	49879108.20	62348885.25	2078.30
67.0	23.56	16822242.79	33812708.01	50634950.79	63293688.49	2109.79
68.0	23.43	16904866.20	34485927.05	51390793.25	64238491.56	2141.28
69.0	23.30	16985874.78	35160760.79	52146635.57	65183294.46	2172.78
70.0	23.18	17065315.41	35837162.35	52902477.76	66128097.20	2204.27
71.0	23.06	17143233.17	36515086.65	53658319.82	67072899.78	2235.76
72.0	22.94	17219671.45	37194490.32	54414161.77	68017702.21	2267.26
73.0	22.83	17294671.98	37875331.63	55170003.61	68962504.51	2298.75
74.0	22.72	17368274.95	38557570.39	55925845.33	69907306.67	2330.24
75.0	22.61	17440519.06	39241167.89	56681686.96	70852108.70	2361.74

76.0	22.50	17511441.61	39926086.87	57437528.48	71796910.60	2393.23
77.0	22.40	17581078.52	40612291.39	58193369.91	72741712.39	2424.72
78.0	22.30	17649464.44	41299746.80	58949211.25	73686514.06	2456.22
79.0	22.21	17716632.79	41988419.71	59705052.49	74631315.62	2487.71
80.0	22.11	17782615.78	42678277.88	60460893.66	75576117.07	2519.20
81.0	22.02	17847444.53	43369290.21	61216734.74	76520918.43	2550.70
82.0	21.93	17911149.06	44061426.69	61972575.75	77465719.68	2582.19
83.0	21.85	17973758.36	44754658.32	62728416.68	78410520.85	2613.68
84.0	21.76	18035300.44	45448957.10	63484257.53	79355321.92	2645.18
85.0	21.68	18095802.34	46144295.98	64240098.32	80300122.90	2676.67
86.0	21.60	18155290.23	46840648.81	64995939.04	81244923.80	2708.16
87.0	21.52	18213789.39	47537990.31	65751779.70	82189724.62	2739.66
88.0	21.44	18271324.26	48236296.03	66507620.29	83134525.36	2771.15
89.0	21.37	18327918.48	48935542.34	67263460.82	84079326.03	2802.64
90.0	21.29	18383594.94	49635706.35	68019301.29	85024126.62	2834.14
91.0	21.22	18438375.79	50336765.92	68775141.71	85968927.14	2865.63
92.0	21.15	18492282.47	51038699.61	69530982.08	86913727.59	2897.12
93.0	21.08	18545335.72	51741486.66	70286822.39	87858527.98	2928.62
94.0	21.02	18597555.67	52445106.98	71042662.65	88803328.31	2960.11
95.0	20.95	18648961.78	53149541.08	71798502.86	89748128.57	2991.60
96.0	20.89	18699572.94	53854770.08	72554343.02	90692928.78	3023.10
97.0	20.83	18749407.45	54560775.69	73310183.14	91637728.92	3054.59
98.0	20.76	18798483.05	55267540.16	74066023.21	92582529.01	3086.08
99.0	20.70	18846816.94	55975046.30	74821863.24	93527329.05	3117.58
100.0	20.65	18894425.81	56683277.42	75577703.23	94472129.03	3149.07

a) Effluent soluble COD, Mx_h biomass, Mx_e endogen residue calculated based on Equation 2-12, Equation 2-13, and Equation 2-14 respectively.
b) MVSS total calculated by sum up the Mx_h biomass and Mx_e endogen
c) Minimum liquid volume calculated by : $MLSS = X_{TSS} \cdot v = P_{XTSS} \cdot SRT$

Complete data for UASB design calculation result presented in Table A- 8

Table A- 8 Complete UASB design parameter data

Design parameter	Unit	Value
Volume gas Holder inside digester tank (optional)		
Max gas produce per day	m^3/day	6354
Gas storage = 0.5* volume gas produce per day	m^3	3177
Height addition	m	12.5
Sludge recovery (estimated)		
HRT	hour	251.904
HRT from digester	days	10.4960
Xu	kg/m^3	40000.0
Qr= Qin x (1-HRT/SRT)/(Xu/XTSS)-1	m^3/day	55.54
R = Qr/Qi		0.37
Q waste		
Qw= MxTSS/(SRT. XTss)	m^3/d	31.49
Q waste from clarifier		
Qw= MxTSS/(SRT. XTss)	m^3/d	23.62
Methane Production rate		
COD degraded	KgCOD/m^3	69.97
Temperature	Celsius	30
CH4 = 0.4 l/g (273.15 +T)/(273.15+35)	l/g	0.39
Methane production per day	m^3/day	4130.28
Total gas Produced per day (65 % methane)	m^3/day	6354.27
Energy Produce		
* energy density of methane at 30 °C	Kj/g	50.1
Methane density at 30 °C	g/L	0.635

Energy produce	Mj/day	131315.8
Nutrient Requirements		
Biomass produce	kg/d	944.64
For N=12% of VSS		0.12
For P=2.4 % of VSS		0.024
N required	kg/d	96.4
P required	kg/d	19.3
Alkalinity req		
Temperature	Celsius	35
CO2 Phase	%	35
Calcium Carbonat needed	mg/L as CaCO3	2100
calcium carbonate in the influent **(assumption)**	mg/L as CaCO3	1300
calcium carbonate req = CaCO3 needed- CaCO3 inff	mg/L as CaCO3	800
Daily addition:	Kg/d as CaCO3	120
Clarifier dimension		
settling rate	m/d	24
Area	m^2	6.25
diameter	m	3
height	m	2.2
Total Height including sludge base	m	3.2
Mechanical design (if using Steel)		
sludge density	kg/m^3	1050
Static Pressure (ps) = ρ. G. H	kPa	103.01
working pressure	kPa	202.64
Total Pressure at base = Ps+P	Kpa	305.6
Max allowable pressure (1.33 x Ptotal)	kPa	406.5
material		carbon steel
working stress of carbon steel	kN/m^2	94408

Joint Efficiency Ej		0.85
Internal radius ri	m	3.4
Allowed corrosion range	mm	2.0
wall thickness = P. ri/(Sej-0.6P)		0.017
total wall thickness	m	0.020
outside tank diameter	m	9.04
Mechanical pumping for mixing		
Unit power = 0.007 KW/m3 of digester volume		
Pump power	KW	13

a) Recovery flowrate (Q_r) calculated by: $Q_r = Qin \frac{1-(HRT/SRT)}{(Xu/XTSS)-1}$

b) Waste flowrate (Q_w) calculated by: $Q_w = \frac{M_{XTSS}}{SRT \cdot XTSS}$

c) Wall thickness: Max allowable pressure x internal radius/ (Joint Efficiency x internal radius – 0.6 max pressure).

d) Daily Methane production: $Methane\ production = COD_{degraded} \cdot Methane\ yield$

Appendix 3: UASB and Anaerobic Contact heat requirement calculation

Table A- 9 listed design parameter used and calculation data for heat requirement in start-up and during operation

Table A- 9 Heat transfer data calculation for Acid phase reactor of Anaerobic Contact

Heat transfer rate during start up	**Unit**	**Value**
Heat from the fluid required		
Volume tank	m^3	1526
mass of liquid inside tank	kg	911,613.96
Height include gas chambers	m	6.0
Diameter	m	18.00
Total surface area, A	m^2	848.21
Density of steel	kg/m^3	8030
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	15
Heat Transfer coeff. From tank/air	W/m^{2}°C	0.91
Heating time	second	36000
Wind velocity	m/s	1
Wind factor		1.4
Transfer rate coeff, U1	W/m^{2}°C	1.274
Qm liq	kW	1595
Heating the tank material		
Tank plate thickness	m	0.02
Volume of the steel	m^3	14.42
Mass of steel	kg	115788
Cp steel	Kj/Kg°C	0.5
Qm tank	kW	24

Heat losses from tank		
Inlet Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
Tamb	Celsius	20
ΔTm = Tm-Tamb	Celsius	7.5
Qm(sides+ top)	kW	8
Total mean heat transfer requirment		
Qstartup = Qm liq + Qm tank +Qm side	kW	1628

Heat Loss During Operation	**Unit**	**Value**
Heat loss from solid surface to atmosphere		
Ambient Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
ΔT	Celsius	7.5
Qm side	kW	8
Heat from the incoming liquid		
mass of liquid	kg/ second	1.77
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	15
Qm liq	kW	112
Total mean heat transfer requirements		
Qoperation = Qm sides + Qm liquid	kW	120

a) T_{amb} is ambient temperature

b) $Q_{m\ liquid} = \frac{m \cdot C_p \cdot \Delta T}{t}$

c) $Q_{m\ side} = \frac{UA\Delta T}{1000}$

Table A- 10 listed design parameter used and calculation data for heat requirement in start-up and during operation for gas phase, Anaerobic Contact reactor.

Table A- 10 Heat energy consumption data of gas phase Anaerobic Contact reactor.

Heat transfer rate during start up		
	Unit	**Value**
Heat from the fluid required		
Volume tank	m^3	5942
mass of liquid inside tank	kg	3,666,845.84
Height include gas chambers	m	9.0
Diameter	m	29.00
Total surface area, A	m^2	2140
Density of steel	kg/m^3	8030
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	15
Heat Transfer coeff. From tank/air	$W/m^{2o}C$	0.91
Heating time	second	36000
Wind velocity	m/s	1
Wind factor		1.4
Transfer rate coeff, U1	$W/m^{2o}C$	1.274
Qm liq	kW	6417
Heating the tank material		
Tank plate thickness	m	0.02

Volume of the steel	m^3	40.68
Mass of steel	kg	326642
Cp steel	Kj/Kg°C	0.5
Qm tank	kW	68
Heat losses from tank		
Inlet Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
Tamb	Celsius	20
ΔTm = Tm-Tamb	Celsius	7.5
Qm(sides+ top)	kW	20
Total mean heat transfer requirement		
Qstartup = Qm liq + Qm tank +Qm side	kW	6505

Heat Loss During Operation

	Unit	Value
Heat loss from solid surface to atmosphere		
Inlet Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
ΔT	Celsius	7.5
Qm side	kW	20
Heat from the incoming liquid		
mass of liquid	kg/ second	1.77
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	0

Qm liq	kW	0
Total mean heat transfer requirements		
Qoperation = Qm sides + Qm liquid	kW	20

a) T_{amb} is ambient temperature

b) $Q_{m\ liquid} = \frac{m \cdot C_p \cdot \Delta T}{t}$

c) $Q_{m\ side} = \frac{UA\Delta T}{1000}$

Table A- 11 listed parameter used and calculation data for heat requirement during start-up and operation for UASB.

Table A- 11 Heat energy consumption data of UASB.

Heat transfer rate during start up

	Unit	Value
Heat from the fluid required		
Volume tank	m^3	636
mass of liquid inside tank	kg	413,280.00
Height include gas chambers	m	10.0
Diameter	m	9.00
Total surface area, A	m^2	409.97
Density of steel	kg/ m^3	8030
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	15
Heat Transfer coeff. From tank/air	W/m^2°C	0.91
Heating time	second	36000
Wind velocity	m/s	1
Wind factor		1.4

Transfer rate coeff, U1	W/m²°C	1.274
Qm liq	kW	723
Heating the tank material		
Tank plate thickness	m	0.02
Volume of the steel	m^3	8.2
Mass of steel	kg	65840
Cp steel	Kj/Kg°C	0.5
Qm tank	kW	14
Heat losses from tank		
Inlet Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
Tamb	Celsius	20
ΔTm = Tm-Tamb	Celsius	7.5
Qm(sides+ top)	kW	4
Total mean heat transfer requirement		
Qstartup = Qm liq + Qm tank +Qm side	kW	741

Heat Loss During Operation

	Unit	Value
Heat from the incoming liquid		
mass of liquid	kg/ second	0.46
Cp liquid	KJ/kg°C	4.2
Δ T	Celsius	15
Qm liq	kW	29
Heat loss from solid surface to atmosphere		

Ambient Temperature	Celsius	20
Operational temp	Celsius	35
Tm	Celsius	27.5
ΔT	Celsius	7.5
Qm side	kW	4
Total mean heat transfer requirements		
Qoperation = Qm sides + Qm article+ Q liquid	kW	33

d) T_{amb} is ambient temperature

a) $Q_{m\ liquid} = \frac{m \cdot C_p \cdot \Delta T}{t}$

b) $Q_{m\ side} = \frac{UA\Delta T}{1000}$