

**DESIGN OF AN ANAEROBIC SYSTEM
TO CONVERT MUNICIPAL AND
INDUSTRIAL WASTEWATER INTO
FUEL**



By

Umair Mazhar

Muhammad Lal Hassan

Abdullah Iqbal

**School of Chemical and Materials Engineering
National University of Sciences and Technology**

2022

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By

Leader - 00000271264 Umair Mazhar

Member 1 - 00000245566 Muhammad Lal Hassan

Member 2 - 00000250222 Abdullah Iqbal

A THESIS

Submitted to

National University of Sciences and Technology

in partial fulfillment of the requirements

for the degree of

B.E CHEMICAL ENGINEERIG

**School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)**

June, 2022

CERTIFICATE

This is to certify that work in this thesis has been completed by **Mr. Umair Mazhar**, **Mr. Muhammad Lal Hassan** and **Mr. Abdullah Iqbal** under the supervision of **Lec. Ayesha Raza** at the school of Chemical and Materials Engineering (SCME), National University of Science and Technology, H-12, Islamabad, Pakistan.

Advisor:

Lec. Ayesha Raza
Department of Chemicals Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Submitted Through:

HOD-----

Department of Chemicals Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Principal/Dean -----

School of Chemical and Materials Engineering
National University of Sciences and Technology

DEDICATION

We dedicate this thesis to our beloved parents who worked hard and made efforts to make our academic career a success and also to our supervisor Lec. Ayesha Raza for her constant support. Thank you very much.

ACKNOWLEDGEMENTS

First and foremost, we are thankful to Almighty Allah who gave us the strength and courage to complete this project. Without his blessings we couldn't have accomplished it.

We wish to express our sincere thanks to Mr. Amir Azam Khan, Principal of the School, for providing us with all the necessary facilities.

We place on record our sincere gratitude to Ms. Ayesha Raza, for lending us her supervision on this project and providing us with her expert sincere and valuable guidance and encouragement towards the task.

Lastly, we place on record, our sense of gratitude to one and all who, directly or indirectly, have lent us their helping hand in making this project a success.

ABSTRACT

Due to a lack of resources and technical capabilities, the World has been experiencing energy problems over the past few years. Furthermore, nonrenewable energy resources are rapidly depleting. As a result, the world has an urgent necessity for an alternate, renewable energy source capable of addressing its energy challenges at this moment.

It is difficult for the authorities to provide sufficient energy to the local community due to low reserves of natural gas worldwide and unstable economic status. Biogas technology can be used as an alternative to provide natural gas / energy to people, particularly those living in rural locations where natural gas is in short supply.

Our final year project mainly focuses at production of Biogas at maximum achievable efficiency with the addition of Manure. Our major source of feed stock is Municipal and Industrial Waste which comprises mainly of organic content. We will run a continuous process at optimum mesophilic conditions after the completion of mass & energy balances to conserve the laws. During the process certain parameters, such as temperature and pH will be controlled according to literature review to achieve maximum efficiency. Biogas produced is later treated using an absorption column for the removal of CO₂ and H₂S traces to achieve pure methane which can be used as electricity, direct fuel for vehicles or for heating purpose.

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INTRODUCTION

1.1 Overview

Lack of coal and petroleum reserves has threatened the supply of fuel worldwide; also, the problem of the disposal of flue gases to the atmosphere has led to research in vast areas to get access of new energy sources such as renewable energy resources. Biogas, wind energy, solar energy, different hydro and thermal energy sources are all renewable sources of energy. Biogas is different from all other renewable energies because of its distinct features, use and ease of control. It is very useful in a way that at one point it is collecting organic wastes from land fill sites to reduce land pollution and simultaneously it is producing fertilizer and water to make use in agricultural irrigation. One of the major advantages of biogas production is that it does not need any technological advancement for energy production and neither it is limited to specific geographical areas.

In developing countries like Pakistan deforestation is a very big problem, most cities depend on charcoal or solid wood for fuel supply which requires cutting of forest. Due to deforestation, fertility of land is decreased by soil erosion. Use of dung is also unhealthy due to the smoke arising from it which causes air pollution. An eco-friendly substitute for energy is needed to fix all the problems.

Waste is an organic material having high calorific and nutritive value to microbes. Efficiency of methane production can be increased by several order of magnitude by mixing municipal and industrial waste with other waste like animal manure. Also, in most of cities and places, waste water is disposed in landfill or discarded which causes the public health hazards and diseases like malaria, cholera, typhoid. Poor management of wastes like uncontrolled dumping of waste has several adverse consequences. It does not only pollute surface and groundwater through leachate but

it further promotes the breeding of flies and mosquitoes which promotes diseases. Also, it emits unpleasant odor & methane gas which is a major greenhouse gas contributing to global warming.

According to official figures, approximately 4.36 BCM of waste water is generated each year in Pakistan, with 1.30 BCM of Industrial waste water, and 3.06 BCM of domestic waste water.

Anaerobic digestion is a controlled biological degradation process which allows efficient capturing & utilization of biogas (approx. 65% methane and 25% carbon dioxide) for energy generation. Different composition of waste water results in varying degrees of methane production. Proportions of these wastes should be determined in order to achieve desired amount of methane gas. Anaerobic digestion is a promising method to treat waste water. There are many factors affecting the design and performance of anaerobic digestion. Most of them are related to feed characteristics, design of reactors and operation conditions in real time. For the designing and operation of digesters, physical and chemical characteristics of the organic wastes are considered because they affect biogas production and process stability during anaerobic digestion. They include moisture content, C: N ratio, volatile solids, nutrient contents, particle size, conditions in biodegradability. The biodegradability of a feed can be calculated by biogas production or methane yield and percentage of solids (total volatile solids) that are consumed in the anaerobic digestion. The biogas or methane yield is measured by the amount of biogas or methane that can be produced per unit of volatile solids contained in the feedstock after subjecting it to anaerobic digestion for a sufficient amount of time under a given temperature.

1.2 Solid Waste Management

Sources of waste all over the world mostly include waste from commercial areas, household waste, and waste from demolition sites, industrial wastes or agricultural

disposals. Waste generations are influenced by the countries size, community type and income of the community.

Solid waste generally consists of paper or cardboard, metal scraps, rubber or plastic, textile waste, glass, animal waste, food waste, leaves, straws, grass, fodder, bones, wood and stones.

According to different studies, 40-50 % of the total solid waste is constituted of organic content. This content when put to landfill, not only generates toxic leachate; contributing towards the depletion of ground water quality, but also releases methane gas in the atmosphere during the biological degradation process. But if we want to look for a solution to this environmental problem, we can say that this major chunk of solid waste is an enormous resource and there is an opportunity of producing energy and quality organic manure.

There is no proper system of solid waste management in Pakistan. Solid waste management system does not exist in most of the rural areas of Pakistan. Solid waste generated mostly is seen in empty plots, place of generation, in drains causing blockages in sewage system or on road sides. We can see open dumping on road / street sites which is a very common practice and local sanitation departments have least interest in waste management and open dumping.

1.3 Biogas in General

Production of biogas takes place when the bacteria break down and bio degrades volatile organic material under anaerobic conditions. Natural generation of biogas is an important part of bio-geochemical carbon cycle. It can be used in both rural and urban areas.

Table 1 Composition of Biogas

Component	Concentration (by Volume)
Methane (CH ₄)	60 – 65 %
Carbon Dioxide (CO ₂)	25 – 30 %
Water (H ₂ O)	2 – 7 %
Hydrogen Sulphide (H ₂ S)	2 %
Ammonia (NH ₃)	0 – 0.05 %
Nitrogen (N ₂)	0 – 2 %
Oxygen (O ₂)	0 – 2 %
Hydrogen (H)	0 – 1 %

1.4 Biogas in Pakistan

About 4% of total area is covered by forest, in which only 5% area is protected. 90% of country's wood production is used as fuel. About 7000 ha of land is reforested in Pakistan every year.

Energy crisis in Pakistan is on its peak these days. Biogas plants in rural areas can play a major role in decreasing the burden on the national energy grids and deforestation. Biogas plants are being built and encouraged with the help of government funds and many other incentives. In our neighboring country India, there are almost two million biogas plants.

Pakistan's 70% population lives in rural areas. Most farmers have two or more cow / buffalos. The dung from these cattle mixed with a specific proportion of waste water can be used to produce biogas in a biogas plant. This biogas can then be used for cooking purposes or to generate electricity through a gas fired engine whereas the left over from this plant can be used as a fertilizer.

About 4,137 biogas plants were installed in Pakistan with the help of the government in the period 1974 to 1987. The government fully funded the first 100 installations and later on, withdrew the financial support. Since then, the growth rate of this technology dropped drastically and only 6,000 biogas plants were installed till the end of 2006.

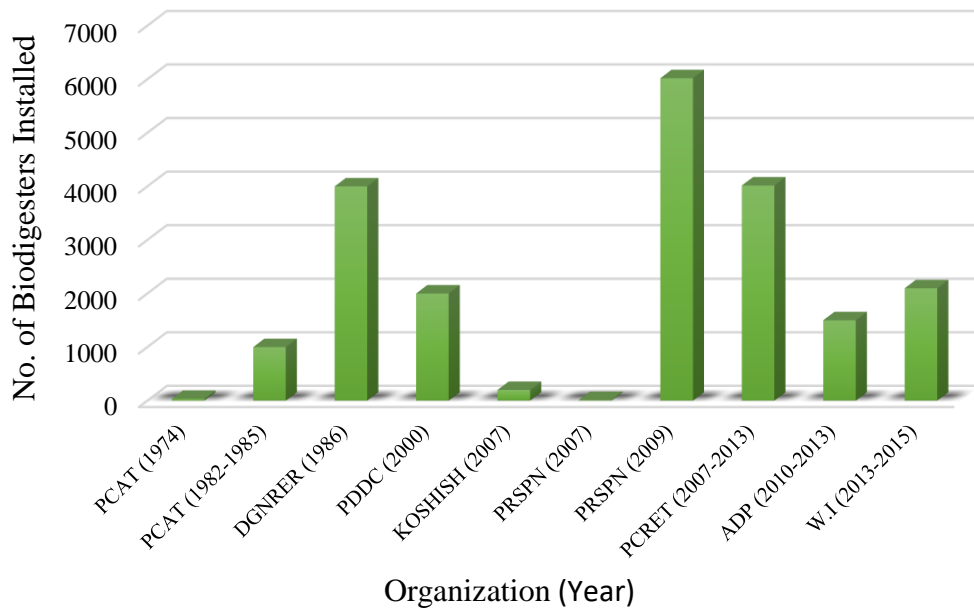


Figure 1 No. of Biogas plants installed in Pakistan since 1974

Pakistan Centre for Renewable Energy Technologies (PCRET) has already installed and supported 4,000 biogas plants with only 50 percent financial contribution from beneficiaries. (SNV, 2007)

There are significant social, economic and environmental benefits of biogas technology. The government of Pakistan through PCRET and Alternative Energy Development Board (AEDB) should take the initiative and announce more funds and support for this proven technology to be a part of our rural society. In parallel, the media should raise the level of awareness among the rural community by highlighting

the benefits of this technology. NGOs and foreign investors should be encouraged to invest in this sector too.

Recently over 4000 biogas plants are being constructed on a small-scale all-over Pakistan. These plants are also easily available in the market. Biogas can also be upgraded after its production which can be used as a vehicle fuel or for electricity or heating purposes. However, high investment cost is a major constraint for the construction and maintenance of biogas plant and thus government support is definitely needed to make an attractive market for biogas plants.

1.5 Characteristics & Properties of Biogas

Composition of biogas depends upon feed material. Biogas is roughly about 20% lighter than air. It has an ignition temperature in range of 650 to 750 °C. An odorless and colorless gas that burns with blue flame similar to LPG gas. Its caloric value is 20 Mega Joules (MJ) /m³ and it usually burns with 60 % efficiency in a conventional biogas stove.

Heating Value of Biogas is about:

- **60 %** of Natural Gas
- **25 %** of Propane

Biogas Energy:

- **6 kWh/m³** = 0.61 liters of Diesel Fuel
- **0.32 - 0.5 m³** of gas / m³ digester volume per day

This gas is useful as fuel to substitute firewood, cow-dung, petrol, LPG, diesel, & electricity, depending on the nature of the task, and local supply conditions and constraints.

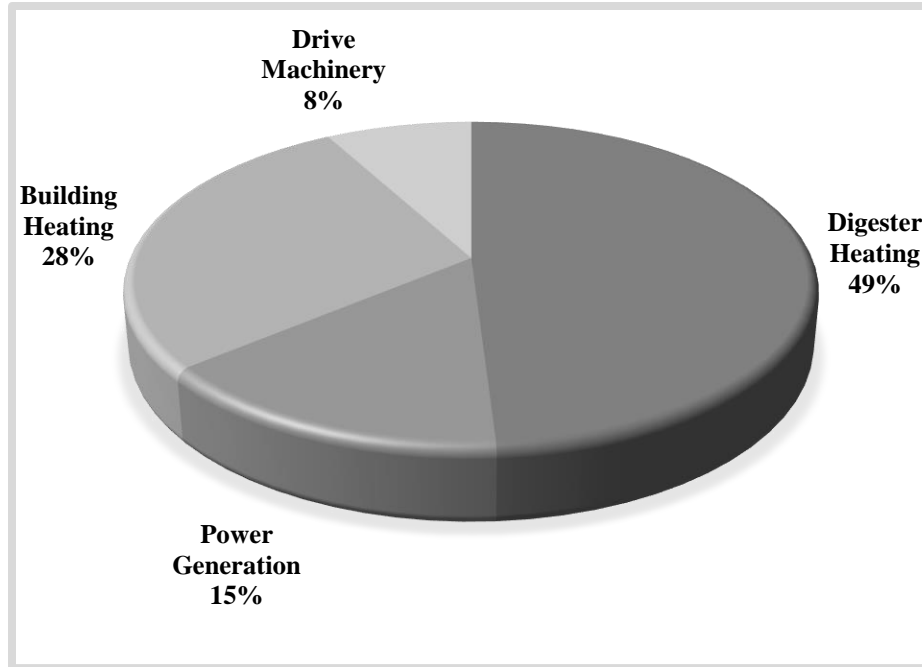


Figure 2 Consumption of Biogas

Biogas digester systems provides a residue organic waste, after its anaerobic digestion (AD) that has superior nutrient qualities over normal organic fertilizer, as it is in the form of NH_3 and can be used as manure. Anaerobic biogas digesters also function as waste disposal systems, particularly for human wastes, and can minimize potential sources of environmental contamination and the spread of pathogens and disease-causing bacteria.

Properties of Biogas:

- Change in volume as a function of temperature and pressure.
- Change in calorific value as function of temperature, pressure and water vapors content.
- Change in water vapor as a function of temperature and pressure.

1.6 Factors Affecting Yield and Production of Biogas

Factors affecting the fermentation process of organic substances under anaerobic condition are:

- Quantity and nature of organic matter
- Temperature
- Acidity (PH value) of substrate
- The flow and dilution of material

Table 2 General Features of Biogas

Parameters	Value
Energy Content	6 – 6.5 kWh/m ³
Fuel Equivalent	0.6 – 0.65 oil / m ³ Biogas
Explosion Limits	6 – 12 % Biogas in Air
Ignition Temperature	650 – 750 °C
Critical Pressure	75 – 89 bar
Critical Temperature	-82.5 °C
Normal Density	1.2 kg / m ³
Smell	Bad Eggs

1.7 Benefits of Biogas Technology

There are many benefits of Biogas technology, some of them are as following

- Production of energy.
- Conversion of organic wastes to high quality fertilizer.
- Improvement in hygienic conditions through reduction of pathogens.
- Environmental advantages through protection of soil, water, air etc.
- Micro-economic benefits by energy and fertilizer substitute.

1.8 Modes of Anaerobic Digestion

- Wet Digestion
- Dry Digestion

1.8.1 Wet Digestion

The wet anaerobic digestion process is applied to liquid waste streams that are conveyed by liquid pumping. Sometimes wet systems are called Low Solids AD (LSAD). The Wet AD process can be done in reactors of two main types, continuously stirred tank reactors (CSTR) and plug flow reactors. The concept behind CSTR is that, through rigorous mixing, the composition or the contents of the reactor in any given spot in the tank is same as in any other spot in the tank. The theory of plug flow, on the other hand, is that the makeup of the contents at the head of the digester is different than that of the material leaving the digester just as the material flows through the digester in the pattern like a plug through a pipe. Wet systems commonly run at total solids levels between 2 and 8 percent. Wet systems will often start with liquid manure or waste biosolids as the backbone of their feedstock load to provide a base load buffering effect for enhanced process stability.

1.8.2 Dry Digestion

Dry digesters are batch operated type of digester used on wastes. Ideal wastes will commonly contain 15-30% solids which imply that they are not liquid enough to store in tanks. Dry digestion can be a good means of generating renewable, biogas energy as pretreatment to a composting system for the remaining solids. Dry Anaerobic Digester units are considered as a "High Solids Anaerobic Digestion Technology" or HSAD. Dry digester is sealed that resembles a garage in its outward appearance. The waste is piled inside the digester chamber and 10 – 15 ft high by the use of automatic conveyor. Unlike with Wet AD systems, the wastes are not ground, chopped or macerated before introducing into the dry digester. Digester contents are heated either by introducing heat through pipes embedded the garage walls or floor or through heat added to the percolate. Optimum digester temperature is in the mesophilic zone (35 °C approximately).

1.9 Incentives to the Project

The main objectives of study are following:

- Production of Biogas from Municipal and Industrial Waste Water and to evaluate the optimum working parameters.
- Making the process of gas production fast with the addition of manure along with Waste Water which should also increase gas production
- Modification of conventional biogas plants to make it eco-friendly.
- To make the process run in Continuous Process.
- Identify and locate the problems in biogas plants and fix them.
- Making the use of nutrient enriched slurry as a fertilizer, filters the CO and traces of H₂S gas from biogas and burn pure methane which is used as a renewable energy.

1.10 Methodology

Two processes can be applied in this process

- Aerobic Digestion
- Anaerobic Digestion

1.10.1 Aerobic Digestion

Bacteria decomposes the organic matter and converts it into carbon dioxide that can be used by plants. Oxygen is used in this process. The end products of aerobic digestion are carbon dioxide, water, and ammonia or nitrates. Some of the properties are as follows:

- Comparatively larger size reactors are required
- High Energy Consumption
- Operating Cost is high
- Less Methane is Produced
- Reaction speed is comparatively fast

1.10.2 Anaerobic Digestion

Here, fermentation is used for fermenting the waste at a specific temperature. Oxygen is not used in anaerobic process. The end products of anaerobic digestion are Methane, Carbon dioxide, and traces of H₂S and other gases. Some of the properties are as follows:

- Comparatively small size reactors are required
- Low Energy Consumption than Aerobic Process
- Operating Cost is Lower
- More Methane is produced in this process
- Reaction speed is comparatively slow

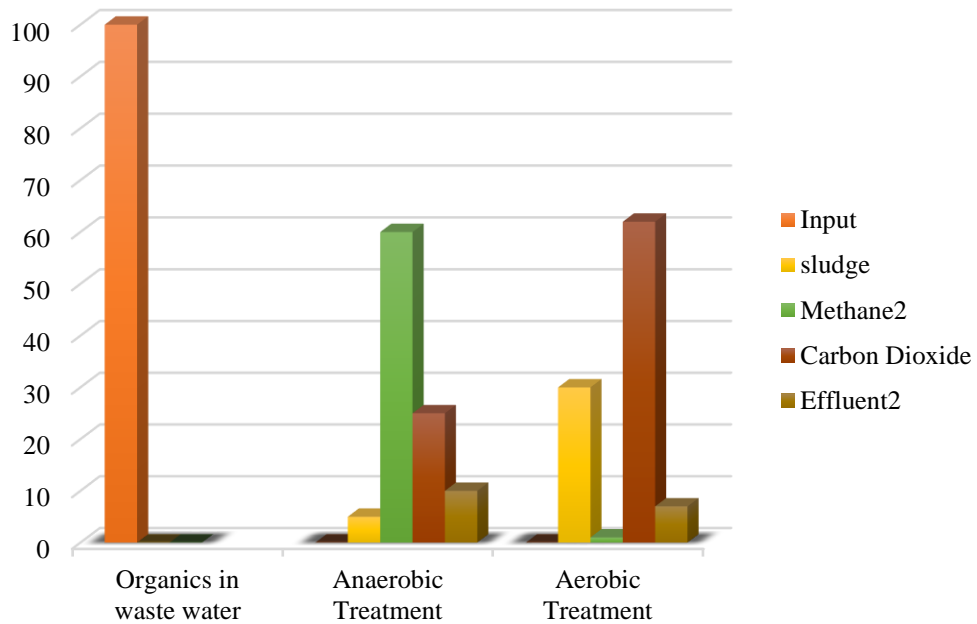


Figure 3 Comparison Between the Methodology

LITERATURE REVIEW

2.1 History of Ad Technology

According to Anecdotal evidence it is known that biogas has been vastly used in heating bath water in Assyria during the late 10th century BC and in Persia during the 16th century. In 17th century, it was discovered by Jan Baptita Van that decaying organic matter evolves flammable gases. It was concluded by Count Alessandro Volta in 1776 that, there was a direct correlation between the amount decaying organic matter and the amount of flammable gas produced. Sir Humphry Davy in 1808, also concluded that there was a certain amount of methane present in the gases that are produced during the AD of waste water along with animal manure.

The first digestion plant was built in Bombay, India in 1859 AD and reached England in 1895 when biogas was recovered from a "carefully designed" sewage treatment facility and used to fuel street lamps. The development of microbiology led to research by Buswell and others in the 1930s to identify anaerobic bacteria and the conditions that promote methane production.

This system was further developed in Germany and the UK in the early 1900s for the treatment of sewage. Centralized drainage systems were being installed in many towns in Europe and anaerobic digestion was seen as a means to reduce the volume of solid matter in the sewage. The gas produced was occasionally used as a source of energy, such as for running vehicles.

Farm-based anaerobic digestion technology is the most common. Approximately, seven million small scale, low-technology digesters are used to provide biogas for heating or cooking purposes. In India and China, there is a growing trend of using

large scale biogas plants which are in operation under the optimum conditions with proper hygiene and process systems in order to generate electricity.

European cities have a good record of using biogas plants and treating suitable farm, industrial, and municipal wastes with more than 600 farm-based digesters being operated currently while some AD plants in Europe have been in operation for more than 20 years. More than 250 of such systems have been installed in Germany alone in the past 5 years.

Factors that influence the success of AD include policies that govern use of waste disposal and local environmental regulations. Many countries have started adapting this method of waste disposal in order to reduce the environmental impacts.

Denmark is known to have the maximum experience of operating large-scale biogas under the optimum conditions and is currently operating 18 centralized plants. In many cases, these facilities use manure, clean organic industrial wastes along with municipal solid waste so to perform co-digestion in order to minimize waste.

Using AD to treat industrial wastewater has tremendously increased in the past few years. It is known that more than 1000 vendor supplied systems are now being operated worldwide or are under construction. In South America, Vinasse which is a co product of sugar-cane, based ethanol production is also being treated to produce Biogas.

AD offers only biological route for recycling matter and nutrients from the organic fraction of MSW. Anaerobic Digestion process is a net energy-producing process, with the production of around 75-150 kWh per ton of MSW input. Municipal Solid Waste digestion technology is now being demonstrated and has been fully commercialized.

There have been many technical problems associated with MSW which includes an increase in HRT, Hydraulic Retention Time. In order to reduce parasitic energy which

is needed in the AD process and digester volume, High-solid digestion (HSD) systems have been developed so to improve the economic performance of MSW systems. Several alternative HSD designs have been developed to operate with total solids (TS) concentrations greater than 30%. These designs employ either external or internal mixing, using biogas or mechanical stirrers; In general, all HSD systems have equivalent performance.

2.2 Production of Biogas by Anaerobic Digestion

Anaerobic digestion is a naturally occurring process in which the volatile organic material is converted into biogas with the help of bacteria. It occurs in marshes and wetlands, and in the digestive tract of ruminants. Biogas is collected and can be used as a potential source of energy. This process occurs under optimum conditions and in the absence of oxygen, through the activities of acid and methane forming bacteria breaking down the organic material and producing methane (CH₄) and carbon dioxide (CO₂) in a gaseous form known as **Biogas**. The environmental advantage of using anaerobic digestion includes reduction of pathogens, odors, flies, and decreasing greenhouse gas emissions (GHG) and other undesirable air emissions. It also stabilizes the manure and reduces BOD. The potential release of nitrates and pathogens into surface waters, the potential for the leaching of nitrates into groundwater and the emission of odors from storage lagoons is considerably reduced with the use of anaerobic digestion.

2.3 Elements of Anaerobic Digestion Systems

Anaerobic digestion systems have been largely used at municipal wastewater facilities for decades, and recently it is being used to process intestinal and municipal wastes. These systems are designed in such a way so to increase the growth of the Methane-forming (methanogen) bacteria that generates CH₄. Using organic wastes as the input, the system produces biogas that contains 60–65% CH₄ and 25–30% CO₂. In general, the overall process includes the following:

2.3.1 Manure Collection and Handling

The manure that needs to be added to the waste is one of the key considerations in the production of Biogas. The right amount of manure concentration gives an added efficiency to the production of biogas.

2.3.2 Pretreatment

Collected Waste Water might undergo pretreatment before it is introduced digester which may include mixing, screening or grit removal. A concrete or metal tank is used to collect manure or water. Proper designing of a mix tank limits the introduction of sand rocks or particulate matter into the anaerobic digester.

2.3.3 Anaerobic Digestion

An anaerobic digester is a vessel which is designed to exclude air in order to promote the growth of methane forming bacteria. A digester can be in the form of a tank or a covered lagoon or may be a more Complex design to suit the conditions, such as a tank with mixer or baffles. It may be designed to heat or mix the organic material. Manure and waste water determine the type of anaerobic digestion technology used. Some technologies may include the removal of impurities Such as hydrogen sulfide (H_2S), which is highly corrosive.

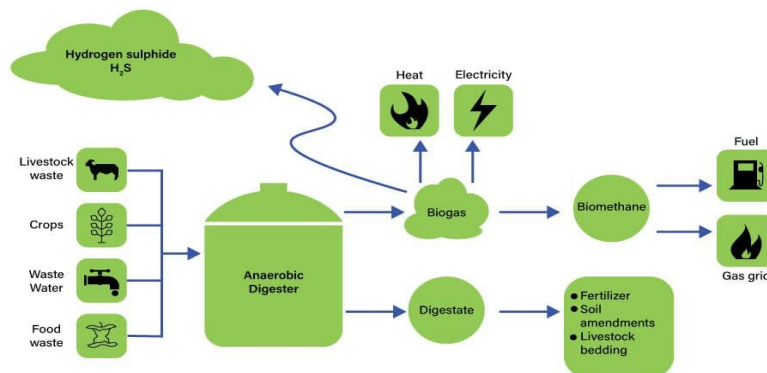


Figure 4 General Overview of the AD System

2.3.4 By-Product Recovery and Effluent Use

This is the non-volatile solid part of the feed which has not digested and become a part of the effluent. It is possible to recover this un-digested fiber from the effluent of digesters. This material can be further treated to be used as fertilizers or in soil amendments as it contains a nitrogen and potassium.

2.3.5 Biogas Recovery

Biogas that is formed in the digester bubbles to the surface of the digester and accumulates beneath a fixed rigid top, a flexible inflatable top, or a floating cover, depending on the type of digester. The collection system then directs the biogas to gas handling sub-systems.

2.3.6 Biogas handling& storage

Biogas is usually pumped or compressed to the operating pressure required by specific applications and then metered to the gas use equipment. Prior to this, biogas may be processed to remove CO₂, H₂S or moisture. Depending on applications, biogas may be stored either before or after processing, at low or high pressures.

2.3.7 Biogas Usage

Recovered biogas can be used directly as fuel for heating or it can be combusted in an engine to generate electricity or flared. If the biogas is upgraded to bio-methane, additional uses may be possible.

2.4 Chemistry of Anaerobic Digestion

Anaerobic digestion is a complex process that involves four stages, as shown in the figure;

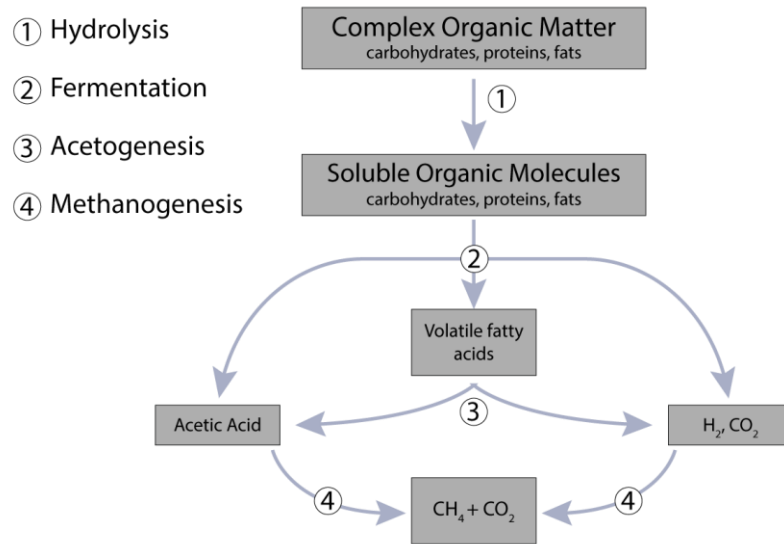


Figure 5 Schematic Representation of the main conversion processes in AD

2.4.1 Hydrolysis

It is the first step, the organic materials are depolymerized, in which the complex polymers such as proteins, carbohydrates and lipids are broken down into monomers such as cellulose, protease, lipase and amylase, by extracellular enzymes. Polysaccharides are converted into sugars. Lipids are converted into small or long chain fatty acids. (Gunaseelam, V.N. 1997)

2.4.2 Acidogenesis

In this step, micro-organisms use fatty acids, amino acid and sugars as substrates to produce organic acids like, acetic, propionic, butyric and small chain fatty acids, alcohols, H₂ & CO₂. (Vindiset al., 2009)

2.4.3 Acetogenesis

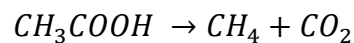
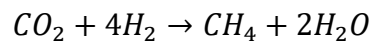
There is no clear distinction between Acetogenesis and Acidogenesis reaction. In this step, the acetogenesis bacteria degrades the hydrogen, sinks acids like propionic, butyric, and valeric acids into formate, acetate, CO₂ and hydrogen. (Rojas et al., 2010)

This step is very important for the production of Biogas, because electron sinks are not utilized by methanogens. Acetogenic bacteria are very slow growing and sensitive to environmental changes. (Gunaseelam, V.N., 1997)

2.4.4 Methanogenesis

H₂, CO₂ and acetic acid are mainly unutilized by methanogens to form methane and carbon dioxide. Methanogens utilize limited number of other substrates like methanol, alcohols fomite to produce methane.

In this stage, most of the organic acids and all of the H₂ is metabolized by methanogenic bacteria to produce 60–65% CH₄ and 25–30% CO₂ called biogas. The methanogenic bacteria are slower growing and more environmentally sensitive (to pH, air, and Temperatures) than the acidogenic bacteria. Typically, the methanogenic bacteria require a pH of above 6, adequate time (typically more than 15 days), and temperatures at or above 35 °C to effectively convert organic acids into biogas. The average amount of time water remains in a digester is called the hydraulic retention time HRT, defined as the digester volume divided by daily influent volume and expressed in hours.



2.5 Environmental Impacts of Anaerobic Digestion

The environmental impacts of anaerobic digestion depend on the manure management system that the digester amends or replaces as well as the actual use of the biogas produced. Combustion of biogas for electricity, or production and use of bio-methane as fuel can provide a number of direct environmental benefits. These include:

- Reduced GHG emissions
- Potential reduction of VOC emissions

- Odor control
- Pathogen and weed seed control
- Improved water quality

One **negative environmental impact** of anaerobic digestion is that,

- Combustion of biogas creates Nitrogen Oxides (NO_x) which regulates air pollutants and contributes to ozone layer. Combustion Of fuel with air produces Nitrogen oxides. NO_x will be produced if any methane containing gas is combusted.

2.5.1 Reduced Greenhouse Gas Emissions

Production of biogas using waste water reduces greenhouse gas emissions in two ways; Firstly, it prevents the release of methane which is a greenhouse gas, when the biogas system is used in the combination with a manure management system under anaerobic conditions. Secondly, the use of fossil fuel, that emits greenhouse gases, is largely replaced by Biogas. The biogas generated from anaerobic digestion contains about 60% CH_4 and it is this component that generates energy. However, methane also contributes to global warming along with being an energy resource.

2.5.2 Reduced Volatile Organic Compound Emissions

In combination with NO_x and Sunlight, Volatile organic compounds produce ozone which is the primary element in air pollution. This makes VOC_s ozone precursor. VOC_s are produced as an intermediate product during the conversion of waste into biogas in the presence of methanogenic bacteria. The amount of CH_4 produced is expected to be directly proportional to the VOC_s produced. An effective methanogenic decomposition is the one in which VOC_s percentage is lower. A well-equipped anaerobic digester may reduce VOC_s by completely transforming them into CH_4 . Some fraction of the remaining VOC_s in the biogas should be eliminated through the combustion of the biogas.

2.5.3 Odor control

Most of the waste water digesters in USA were built to address odor complaints. H₂S, VOCs and ammonia emissions from the waste are the main cause of odor problems. Anaerobic digestion is a good and a cost-effective method to deal with the odor problem particularly if the H₂S in the biogas is recovered for further treatment and is scrubbed off from the biogas.

2.5.4 Control of Pathogens and Weed Seeds

Pathogens and weed seeds get de-natured at high temperatures, therefore making thermophilic and mesophilic conditions in the digester, suitable for effective reduction in number of pathogens and weed seeds. In a mesophilic digester, at a solid retention time of 20 days, the Pathogen reduction is greater than 99%. Thermophilic temperatures essentially result in the complete elimination of pathogens. Covered-lagoon digesters, which operate at ambient temperatures, have a more modest effect on weed seeds and pathogens.

2.5.5 Improved Water Quality

An anaerobic digester will have minimal effect on the total nutrient content of the digested manure. However, the chemical form of some of the nutrients will be changed. A digester decomposes organic materials; converting approximately half or more of the organic nitrogen (org-N) into NH₃-N. Some phosphorus (P) and potassium (K) are released into solution by decomposing material. A minimal amount of the P and K will settle as sludge in plug flow and complete mix digesters. However, 30% to 40% of the P and K are retained in covered-lagoon digesters in the accumulated sludge. Dissolved and suspended nutrients are of lesser concern as they will flow through the digester. The anaerobic digestion process is an effective way to reduce high BOD in the effluent. Biological oxygen demand is a measure of the amount of oxygen used by microorganisms in the biochemical Oxidation of organic matter.

Anaerobic Process can remove 70 – 90 % of the BOD in high strength waste water at a lower cost in terms of both land and energy inputs than aerated systems.

2.6 Operating Parameters & Optimum Conditions in Biogas Production

Many factors affect the anaerobic digestion process, controlling these factors can enhance the anaerobic process. These factors include:

- Type of Organic waste
- Temperature
- Waste particle size
- Presence of toxic material
- pH
- Hydraulic retention time
- Carbon to nitrogen ratio
- Solid retention time
- Mixing

2.6.1 Type of organic waste

In the digester not all waste is converted to biogas. For example, lignin cannot be degraded through anaerobic bacteria and settles down in the sludge part of the fermenter. The waste which is not converted to biogas is the non-volatile inorganic waste which mostly contains nitrogen and potassium and can be treated and processed further to be used as a fertilizer. Waste that contains huge amount of sulfur or nitrogen results in large amount of unwanted ammonia and hydrogen sulfide. The waste that is not completely soluble in water degrades very slowly.

5.6.2 Temperature

The three majorly used temperature conditions in anaerobic digestion are:

- *Psychrophilic*

- Temp: (10 °C – 20 °C)
- *Mesophilic*
 - Temp: (30 °C – 40 °C)
- *Thermophilic*
 - Temp: (40 °C – 55 °C)

For achieving successful anaerobic digestion, several physical and chemical factors must be considered. The most important physical factor is **temperature**. According to research, it was seen that with increase in temperature, biogas production also increases. However, *mesophilic conditions* are the most favorable.

2.6.3 Size Reduction

Size reduction is very important parameter in anaerobic digestion. The optimum size of waste must be between 10mm to 12mm; when it enters the digester so to make the process as efficient as possible and for the better solubility in the water. Pumping of waste after size reduction is much easier as compared to raw waste. We can avoid blockage of pipes after shredding. Shredding is not only help in pumping but also increase the surface area for bacteria in reaction. Through shredding, biodegrading can easily be accomplished. It also helps in getting the consistent feed.

2.6.4 Toxic Material

The toxic material level should be maintained at optimum conditions. Anaerobic Digestion process can handle small quantity of toxic material. These toxic materials are avoided because these materials can inhibit the process.

2.6.5 pH

pH plays a vital role in anaerobic digestion. Methane producing bacteria are directly affected with the hydrogen ion concentration. Digestion is completely prohibited by access of acidity. Bacteria produce methane in the pH range of 6.8 – 7.2. At the start, acid forming bacteria begins to produce acids which break down into methane by

methanogens. If acids formation is still increasing and exceeds the consumption level of methanogens, then these acids decrease the pH. When pH decreases, the carbon dioxide contents start to increase while methane production decreases. Normally to keep the anaerobic digestion balance, lime (NaOH) is added. However, a level of lime should be maintained carefully because excess lime results in precipitation of sodium carbonate. Sodium bicarbonate can also be used to maintain the pH.

2.6.6 Hydraulic Retention Time

Hydraulic retention time means how many hours the waste water remains in the digester. This retention time plays an important role in anaerobic digestion, because it tells us the time factor for bacteria growth which on the other hand tells the conversion of biodegradation of organic material into methane.

Anaerobic digestion depends on the biological activity of relatively slowly reproducing methanogenic bacteria. These bacteria must be given sufficient time to reproduce, so that they can replace cells lost with the effluent sludge, and adjust their population size to follow fluctuations in organic loading. If the rate of bacteria lost from the digester with the effluent slurry exceeds the growth rate of the bacteria, the bacterial population in the digester will be washed out of the system. This washout is avoided by maintaining sufficient retention time for solids ensuring that the bacterial cells remain in optimal concentration within the digester.

2.6.7 Solid Retention Time

The solid retention time is one of the important factors in digestion process. It is equal to the number of solids maintained in the digester divided by the amount of the solid drained. Conversion of volatile solids into methane depends on solid retention time. If solid retention time is very low then it shows that there is no sufficient time for bacteria to grow. Bacteria loss in effluent increases. If bacteria loss rate exceeded than bacteria growth rate; wash out occurs.

$$SRT = \frac{\text{Solids Maintained}}{\text{Solids Drained}}$$

2.6.8 Carbon to Nitrogen Ratio

Carbon to nitrogen ratio is also a main factor that affects the anaerobic digestion process. Carbon provides energy to microbes while nitrogen enhances the microbial growth. If we do not maintain the quantity of nitrogen, then microbial growth is inhibited which have adverse effect on the methane production. If the carbon content increases and nitrogen content decreases this will result in increase in energy level which inhibits microbial growth. Carbon is utilized 30 times more than that of nitrogen. Therefore, carbon to nitrogen ratio should be maintained at **30:1**

2.6.9 Mixing

Mixing plays an important role in achieving the optimum anaerobic process. Mixing keeps uniformity in substrate concentration and in temperature. Mixing helps avoid solid deposition in anaerobic digester.

2.7 Types of Biogas Digesters

Some of the common types of biogas digesters are as follows:

- Floating-drum Digester
- Balloon Digester
- Earth-pit Digester
- Fixed-dome Digester
- ***UASB Digester***

2.7.1 Floating-drum Digester

Floating drum biogas plants have a digester and a moving gas holder. The gasholder moves either directly on the fermentation slurry or in a water jacket. Gas is collected in gas drum, which rises on positive pressure. If gas is taken off, the drum falls again. Gas drum is saved from tilting by a guide frame.

Table 3 Pros & Cons of Floating Drum Digester

Pros	Cons
It has a very simple and easy understanding operation.	Very high construction cost of floating-drum.
Gas pressure inside remains constant.	The steel parts are easily corroded
Capacity of stored gas can be seen directly.	It has a very short life.
Not many mistakes in construction.	

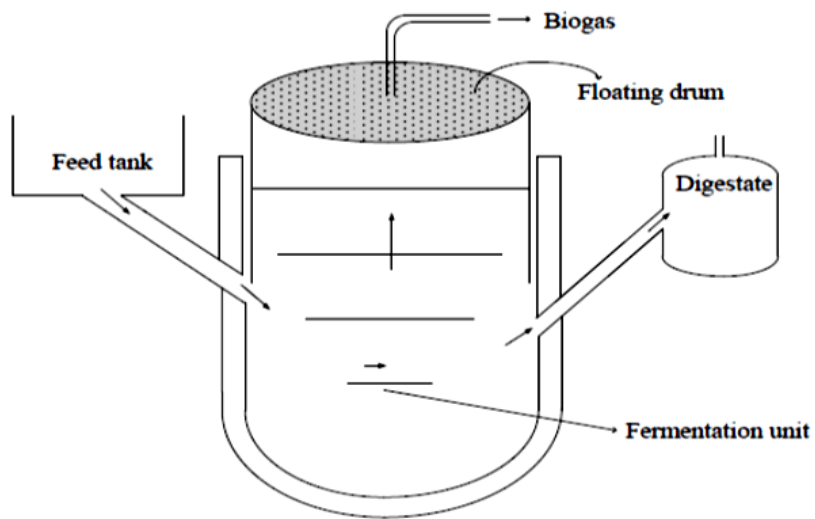


Figure 6 Schematic of Floating Drum Digester

2.7.2 Balloon Digester

This plant consists of a heat-sealed plastic bag (balloon), digester and gas-holder combined. Gas is stored in upper portion of balloon. The inlet and outlet are connected directly to the upper portion of the balloon. Gas pressure is increased by putting weights on the balloon. If the gas pressure is increased to a limit that the balloon cannot withstand, it can damage the skin. So, safety valves are added. A gas pump is needed if there are high gas pressures.

Table 4 Pros & Cons of Balloon Digester

Pros	Cons
Fabrication can be done at low cost	Gas pumps are required where there is low gas pressure
Cleaning of plant is not complicated	Scum is not easily removed during operation
Construction cost is cheap	Plastic balloon plants have short life span and they are easily damaged
The plant is suitable in areas with high ground water	Local craftsmen are not technically strong to repair the damaged balloon.

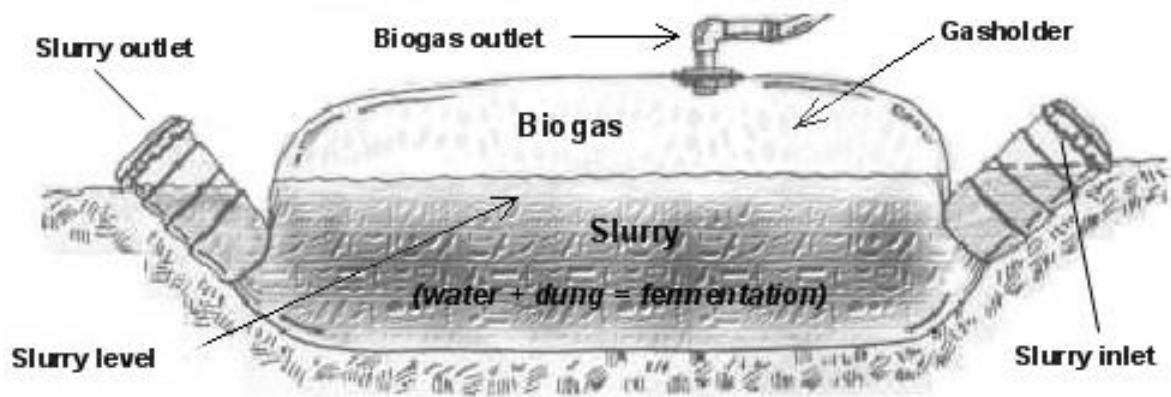


Figure 7 Schematic of Balloon Digester

2.7.3 Earth Pit Digester

This is also called masonry digester and walls are plastered with cement. Enforced is used on the edge of the pit which also used as gas holder. (F. V., & Euler, H. 1998)

Table 5 Pros & Cons of Earth Pit Digester

Pros	Cons
Installation cost is low (20% of floating drum plant)	A short life which works only in certain type of soils
Very high potential for self help	These are installed only in impermeable soil above ground water table.

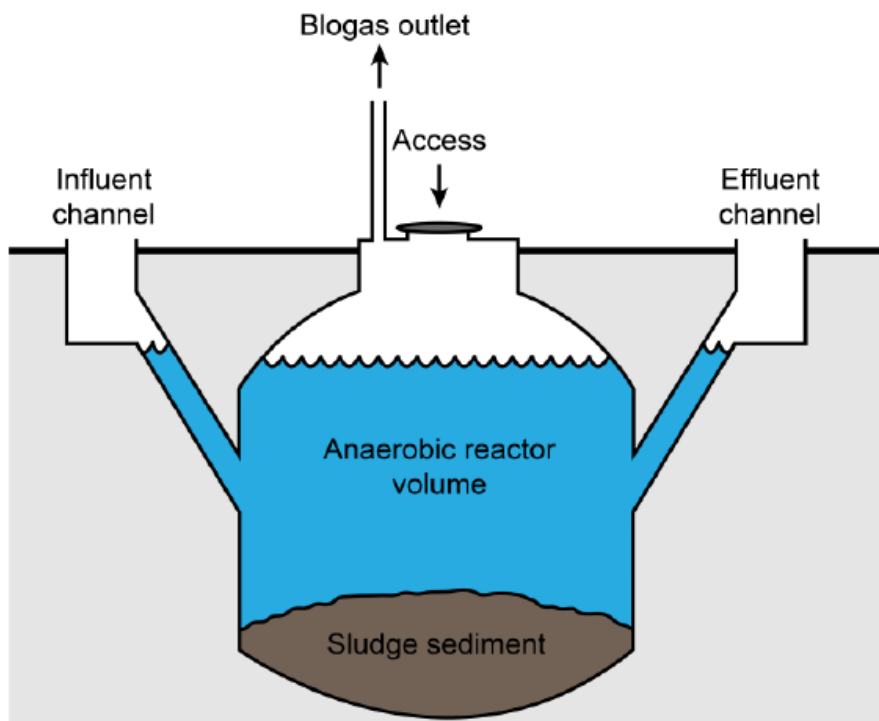


Figure 8 Diagram of Earth Pit Digester

2.7.4 Fixed dome Digester

This is a low-cost Biogas plant which consists of a digester and fixed or non-movable has Holder which is on the top of digester. These parts are made of steel. These types of plants are protected from low temperature during nights and cold weathers.

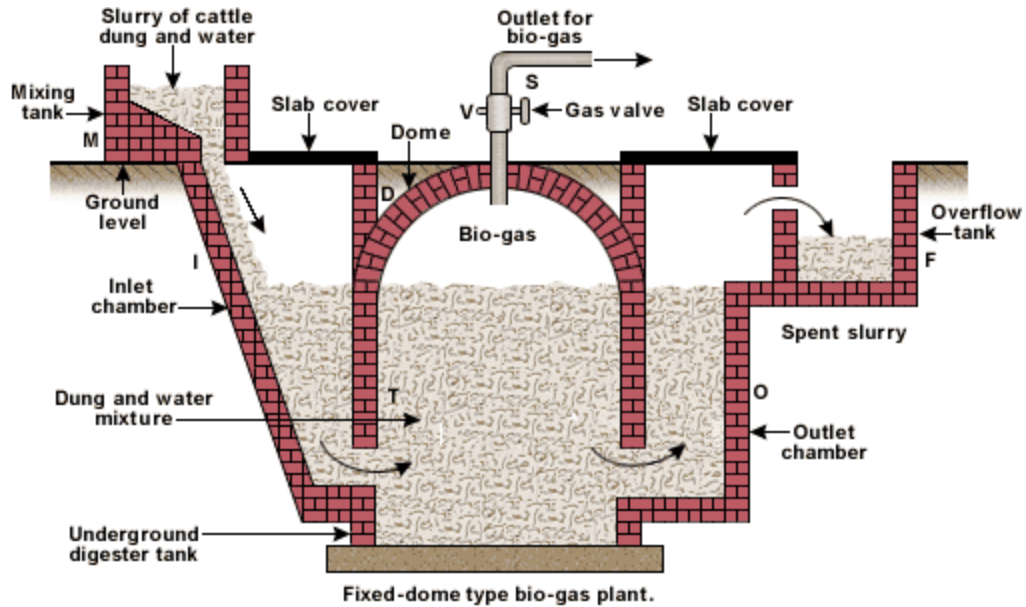


Figure 9 Schematic of Fixed Dom Digester

2.7.5 Up – flow Anaerobic Sludge Blanket Digester (UASB)

A UASB digester is the most widely used anaerobic process for industrial wastewater treatment. In a UASB digester, anaerobic sludge in the form of granules is suspended in the bottom of the digester and the flow of wastewater is upward through the sludge blanket. In a UASB digester, separate Acidogenesis and Methanogenesis processes improve digester performance and help in the retention of biomass, which in turn allows the recovery of biomass during hydraulic and organic shock.

UASB digester is a widely employed anaerobic system for sewage treatment in tropical countries including Latin America and India. It has been recognized as the third most popular and extensively used sewage treatment technology in Latin America where Brazil alone is known to have more than 650 full-scale UASB installations (Daverey et al., 2019).

❖ Advantages:

- Ability to withstand organic shock loads
- Requires smaller digester volume

- Simple construction and low operation and maintenance cost.
- Robustness in treatment efficiency and wide applicability from very small to very large scale
- Energy is generated as methane/hydrogen gas. Energy generated can be used to heat the boilers to reduce operation costs. Less energy demand when external temperature control is not required
- Less CO₂ emissions due to less energy requirement and additional energy production in the form of biogas that can be used to run the system
- Ability to treat sewage due to availability of macro- and micronutrients and stability of pH without addition of any chemicals

❖ Disadvantages

- Long startup time is required due to the slow growth rate of microorganisms in case activated sludge is not amply available.
- Needs post treatment as pathogens are not removed completely, except for helminths eggs that are successfully entrapped in the sludge. Incomplete removal of nutrients and therefore needing post treatment.
- A considerable portion of biogas produced may be dissolved in the effluent whose recovery is needed

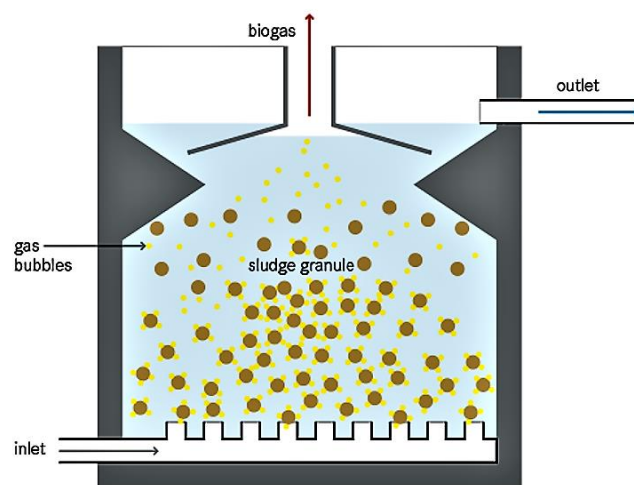


Figure 10 Schematic of UASB Digester

2.8 Methods of Adding Feed

The Main part/equipment of an anaerobic biogas plant is known as digester. This is an airtight tank which contains organic waste, and which can be emptied of digested slurry with some means of collecting the produced gas. Design differences mainly depend on the type of organic waste to be used as raw material, the temperatures to be used in digestion and the materials available for construction. (Habmigern, 2003)

Feed is added in two types:

- Batch Feeding
- Continuous Feeding

2.8.1 Batch Feeding

Anaerobic digestion is performed either in a batch process or in continuous process. In batch process feed is added to the digester at the start of the process. Reactor is closed for the duration of the process. Inoculation is required in batch processing with already processed material to start digestion. Pattern of Biogas production is normally distributed over the period of time.

Major disadvantage of batch reactor is that there are severe odor issues if the digester is opened and closed before the completion of process. Advanced type of batch approach has less odor problems because they are integrated with in vessel composting. Here inoculation takes place by the help of re circulated degasified percolate. After Complete anaerobic digestion, biomass is present in the reactor which is later used for in-vessel composting before it is opened. Batch reactor is cheaper than continuous reactor since batch digestion is quite simple and requires less equipment and design work. More than one batch reactor can be used which ensures continuous production of biogas.

Dependent on the waste material and operating temperature, a batch digester will start producing biogas after two to four weeks, slowly increase in production then drop off after three or four months. Batch digesters are therefore best operated in

groups, so that at least one is always producing useful quantities of gas. (Yadvikaet al., 2004).

2.8.2 Continuous Feeding

In continuous feeding, organic matter is continuously added (continuous complete mixed). The finished products are constantly removed which results in continuous production of biogas. Single or multi digesters in line can be used. Examples are

- Continuous stirred-tank reactors
- Up flow anaerobic sludge blankets
- Expanded granular sludge beds
- Internal circulation reactors.

Complete anaerobic digestion of waste water takes roughly about 8 weeks at normally warm temperatures. One third of the total biogas will be produced in the first week, another quarter in the second week and the remainder of the biogas production will be produced in the remaining 6 weeks.

Gas production can be accelerated and made more consistent by continuously feeding the digester with small amounts of cow dung daily. This will also preserve the nitrogen level in the slurry for use as fertilize. (Igoniet al., 2008)

In continuous feeding system, it is essential to ensure that the digester is big enough to hold all the material that will be fed through in a whole digestion cycle. One solution is to use a double digester, consuming the waste in two stages, with the main part of the biogas (methane) being produced in the first stage and the second stage finishing the digestion at a slower rate, but still producing another 20 % or so of the total biogas. (Habmigernet al., 2003)

2.9 Types of Anaerobic Digestion

- ⇒ Mesophilic
- ⇒ Thermophilic

2.9.1 Mesophilic Anaerobic Digestion

Temperature ranges for mesophilic digestion are between 25-40 °C. This type of digestion takes 25-30 days for bio degradation. Mesophilic digestion is sturdier and more tolerant than thermophilic anaerobic digestion but biogas generation is less. Big advantage of mesophilic anaerobic digestion over thermophilic digestion is that it is very Cheap and does not require any outer heat source for complete digestion. It takes its own time and produces same quality biogas as of thermophilic digestion

2.9.2 Thermophilic Anaerobic Digestion

Thermophilic digester is a kind of bio digester that works in temperatures above 50 °C. Advantages of thermophilic digestion are that:

- It does not require agitation.
- It is faster in fermentation than a mesophilic digester.
- It is around 6 to 10 times faster than mesophilic.

Thermophilic digestion occurs between 50-65 °C. Digestion process is very fast in the thermophilic process. Biogas generation starts in 8 to 10 days. High biogas production is achieved in this process but it is very costly because high degree of energy input is required. During this process, about 30-60% of the digestible solids are converted into biogas.

PROCESS DESCRIPTION

3.1 Path Flow

3.1.1 Pretreatment

The waste water readings include the quantity of waste water produced by 26 sectors of Islamabad. It is first processed to move inorganic non-biodegradable solid material such as wood, glass or plastic through a screener. After pretreatment processes, it is collected into the storage tank. Around 25136.9 kg of waste water is treated per hour. It is then fed to the Mixer where it gets mixed with 6% of Manure to adjust the C:N ratio. The mixer also provides a uniformity of water. An electric heater has also been installed, so that the temperature of water can be maintained in winters.

3.1.2 Digestion

After slurry formation, the mixture is passed into the biogas digester where anaerobic digestion takes place and all the four reactions take place under optimum conditions which are under standard pressure conditions and temperature of 35 °C. After the retention time of 13 – 14 days; all the sludge has been consumed. Water keeps ejecting out with an HRT of 14 hours. Continuous production of gas has been achieved.

3.1.3 Absorption Column

The gas is then directed to post-treatment process. It is first directed into the Absorber where the solvent MEA absorbs 95% CO₂ and H₂S. The treated Biogas is released from the top whereas the rich MEA solution is passed onto the stripper where 99% CO₂ and H₂S are recovered for further treatment. The MEA is regenerated in the stripper through steam re boiler and is re-used in the absorber. The treated biogas at the top of the absorber is passed to the condensate trap where

99.5% moisture is knocked out to bring about the final treated biogas with the methane quantity increased from 65% to 91.7%.

3.2 Objectives of the Project

3.2.1 Understanding the title

The first objective is the understanding of the project title; that why have we opted this project and what can be the future endeavors of this project. The project basically involves the conversation of waste water into energy which will eventually decrease the land and air pollution. Resultantly GHG will be reduced in the environment.

In addition, enough amount of heat energy will be generated on hourly basis that can be used to produce steam and rotate the turbine to produce electricity; whereas cost of production would be much lesser comparatively. This will help meet the electrical needs of the society.

The *SDGs (Sustainable Development Goals)* that are linked to our project are as follows:

Sustainable Development Goals	
No. 6	Climate and Sanitation
No. 7	Affordable & Clean Energy
No. 12	Responsible Consumption & Production
No. 13	Climate Action

3.2.2 PFD Design

This objective involves the designing of Process Flow Diagram which would be followed throughout the project. PFD includes the necessary equipment and the flow of our feed through different stages.

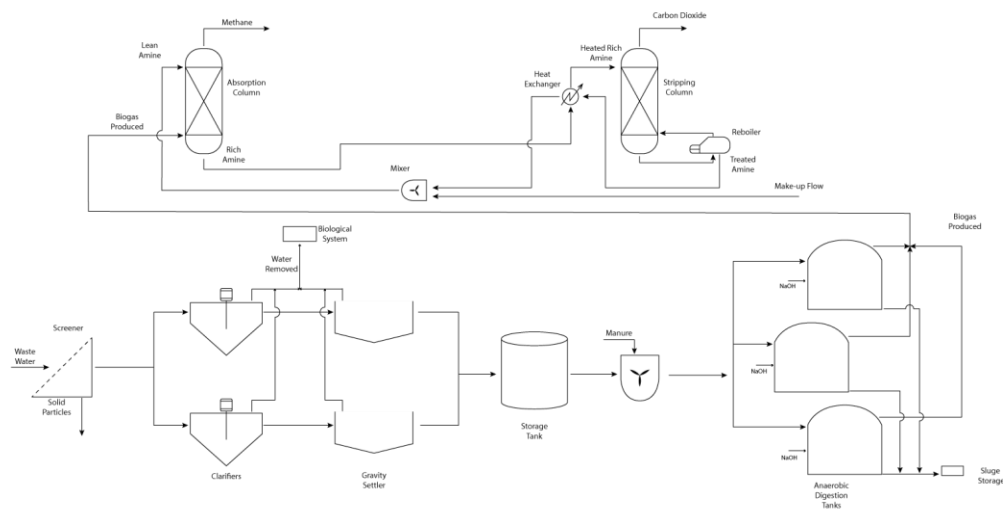


Figure 11 Process Flow Diagram

6.2.3 Material & Energy Balance

Material balance includes the law of conservation of mass; to check whether the mass going in the system is equal to the amount of mass coming out of it. For a steady state process; accumulation would be zero. So, the final equation that is further used is

$$In + Generation = Out - Consumption$$

Energy Balance includes the law of conservation of Energy. As our project includes generation of energy; so, the energy required would be lesser than the energy generated. Hence concluding that, this project is feasible in the form of energy generation. The equations used are as:

$$\Delta U + \Delta E_k + \Delta E_p = Q - W_s + W_{fl}$$

$$\Delta H = Q + W \quad Q = mc_p \Delta T$$

3.2.4 Design of Equipment

After mass and energy conservation; the project proceeds to the design of necessary equipment to find out their required specifications.

Table 6 Major Equipment in process

Equipment	Key Focus	Method	Assistance
Mixer	Mixing waste water with manure forming a uniform slurry	Mixing	Manure
UASB Digester	Produces maximum amount of Biogas in a continuous process	Anaerobic Digestion	Absence of Oxygen
Absorber	Absorbs CO ₂ and H ₂ S content in the Biogas	Physical Absorption	MEA Solvent
Striper	Recovers CO ₂ and H ₂ S and regenerates MEA Solvent	Flashing	Steam
Heat Exchanger	To increase the temperature of Rich Amine	Conductive & Convective Heat Transfer	Lean Amine

3.2.5 Simulation

The process objective involves the simulation of the process flow diagram on the **ASPEN PLUS** and to check the feasibility of the equipment design. This step also includes to find out any possible changes in the theoretical flow rates or the composition of gas as done in the material and energy Balance.

3.2.6 Economic Analysis

The process timeline is then followed by Cost / Economic Analysis to find out whether the project is feasible to install or not as per industrial standards. This objective also

includes the calculation of Break-Even Point, the capital cost, Annual Revenue and the Rate of Return of the Project.

3.2.7 HAZOP Analysis

This Objective; the last one; Hazard and Operability Analysis; includes the safety data sheets to check for possible failures in the plant and provide the safeguard actions that could be taken in that case. This will help the project in a sense that these preventive measures would be taken as a priority.

3.3 Optimum Conditions

These are the optimum conditions which are best suitable for the production of Biogas, and these are also the conditions that we applying in our process.

Table 7 Optimum Conditions for Digester

Parameters	Range
Temperature	30 – 40 °C
pH	6.8 – 7.2
Total Solids	8 – 15 %
Volatile Solids	Above 80 %

3.4 Biogas Composition from Digester

Since the Methane quantity has been increased; the gas can be used as natural gas or can be used in heating purposes or to generate electricity. It can also be directly utilized as gasoline in the engine of vehicles.

Table 8 Composition of Biogas from Digester

Gases	Composition	Volume (m ³)	Mass flow Rate (kg/hr)	Molar Flow Rate (kmol/hr)
CH₄	0.65	623.5	416.5	26.04
CO₂	0.25	239.8	441.7	10.04
H₂S	0.0005	0.5	0.68	0.02
H₂O	0.06	57.55	57.43	2.57
N₂	0.0195	18.7	21.82	0.78
O₂	0.01	9.6	12.77	0.40
H₂	0.005	4.8	0.427	0.21
NH₃	0.005	4.80	3.44	0.20
Total	100	960	954.77	40.26

MATERIAL BALANCE

Wastewater flowrate = **64324779.1 kg / day**

Table 9 Composition of Waste water

Component	Composition
TSS	423 mg/L
COD	470 mg/L
BOD	300mg/L
VSS	82% of TSS

4.1 Material Balance on Screener

Wastewater flowrate = 64324779.1 kg/day

Removed in screener = 2%

Amount of wastewater removed in screener = 1287040 kg/day

Amount of wastewater to primary sedimentation tank = **63064960 kg/day**

4.2 Material Balance on Pre-Treatment

After pre-treatment processes, the composition of wastewater is as follows

Water flowrate = 24,051 kg/hr

TSS = **1086.11 kg/hr**

Total flowrate = 25,136.97 kg/hr

4.3 Material Balance on Mixer

Table 10 Feed to the Mixer

Parameters	% Composition	Total Amount
Total weight (kg/hr)		25136.97
Total solids (kg/hr)		1086.11
Water content		24,051
Volatile solids	82	890.61

4.3.1 Composition of volatile solids

Table 11 Composition of VS

Component	% Composition	Amount
Fats	17	151.4
Protein	21	187
Carbohydrate	62	552.2

4.3.2 Composition of Manure

Table 12 Composition of Manure

Parameters	Manure Composition	Amount of Manure
Total Weight (kg/day)	100	1,667
Total Solids	8	133.34
Water Content	92	1533.3
Volatile Solids (Carbohydrates)	83	110.67
COD (mg/L)	6100	
BOD (mg/L)	4290	
Nitrogen in mg/L	30-36	
Phosphorous in mg/L	10	

4.4 Material Balance on Digester

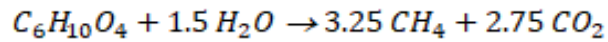
4.4.1 Inlet composition to Digester

Table 13 Feed to Digester

Parameter	Mass Flowrate (kg/hr)	% Composition
Total Stream to the Mixer	26,804	100
Water Contents to the Mixer	25,584	95.5
Total Solids	1219.44	4.5
Total VS	1001.277	3.7
Fat Concentration	151.4	0.2
Protein Concentration	187.0	0.2
Carbohydrates Concentration	662.8	0.7

4.4.2 Reactions involved in the digester

1. Carbohydrates



Molecular weight of $C_6H_{10}O_4 = 146.14$ g/mol

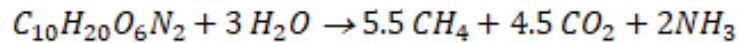
Number of moles of $C_6H_{10}O_4 = \frac{662.8}{146.14} = 4.5$ k.mol

Number of moles of $CH_4 = 4.5 \times 3.25 = 14.7$ k.mol

Mass of $CH_4 = 14.7 \times 16 = 236$ kg/hr

Volume of CH_4 produced = $\frac{236}{0.668} = 353.1$ m³/hr

2. Protein



Molecular weight of $C_{10}H_{20}O_6N_2 = 264.3$ g/mol

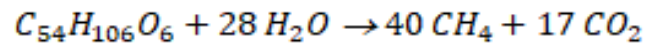
Number of moles of $C_{10}H_{20}O_6N_2 = \frac{187}{264.3} = 0.8$ k.mol

Number of moles of $CH_4 = 0.8 \times 5.5 = 4.2$ k.mol

Mass of $CH_4 = 4.2 \times 16 = 66.8$ kg/hr

Volume of CH_4 produced = $\frac{66.8}{0.668} = \mathbf{100\ m^3/hr}$

3. Fats



Molecular weight of $C_{54}H_{106}O_6 = 851.41$ g/mol

Number of moles of $C_{54}H_{106}O_6 = \frac{151.4}{851.41} = 0.2$ k.mol

Number of moles of $CH_4 = 0.2 \times 40 = 7.1$ k.mol

Mass of $CH_4 = 7.1 \times 16 = 113.8$ kg/hr

Volume of CH_4 produced = $\frac{113.8}{0.668} = \mathbf{170.4\ m^3/hr}$

Total volume of CH_4 produced = $\mathbf{623.5\ m^3/hr}$

Assuming 65% of CH_4 in Biogas, then

Total Biogas produced = $\mathbf{959.2\ m^3/hr}$

4.4.3 Composition of Biogas produced

Table 14 Composition of Biogas Produced

Gases	Composition	Volume (m ³)	Mass flow rate (kg/hr)	Molecular mass (kg/mol)	Molar flow rate (kmol/hr)
CH₄	0.65	623.5	416.5	16	26.04
CO₂	0.25	239.8	441.7	44	10.04
H₂S	0.0005	0.5	0.68	34	0.02
H₂O	0.06	57.55	57.43	18	2.57
N₂	0.0195	18.7	21.82	28	0.78
O₂	0.01	9.6	12.77	32	0.40
H₂	0.005	4.8	0.427	2	0.21
NH₃	0.005	4.80	3.44	17	0.20
Total	100	960	954.77		40.26

$$\text{Density of Biogas} = [(623.5 * 0.668) + (239.8 * 1.842) + (0.5 * 1.36) + (4.80 * 0.717) + (57.55 * 0.998) + (18.7 * 1.167) + (9.6 * 1.331) + (4.8 * 0.089)] / 954.7$$

Density of Biogas produced = **0.984 kg/m³**

4.5 Material Balance on Absorber

Table 15 Feed to Absorber

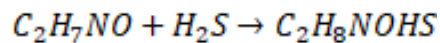
Components	Mass flow rate (kg/hr)	Molar flow rate (kmol/hr)
<i>CH₄</i>	416.5	26.04
<i>CO₂</i>	441.7	10.04
<i>H₂S</i>	0.68	0.02
<i>H₂O</i>	57.43	2.57
<i>N₂</i>	21.82	0.78
<i>O₂</i>	12.77	0.40
<i>H₂</i>	0.427	0.21
<i>NH₃</i>	3.44	0.20
Total	954.77	40.26

Basis: 1 hour operation

Absorber system: MEA is **14.5%** at the bottom liquid solution after absorption

Assumption: only CO₂ and H₂S is absorbed, and all other gases act as inert

4.5.1 H₂S Balance



Moles of H₂S = 0.02 kmol

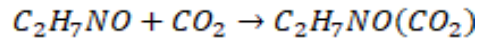
By equation

Mole ratio is 1:1

So, for 95% conversion of H₂S

No. of Moles of H₂S absorbed = 0.95 x 0.02 = 0.019 kmol

4.5.2 CO₂ Balance



No of moles of CO₂ = 10.04 kmol

By reaction equation

Mole ratio is 1:1

So, for 95% reaction of CO₂ with MEA

Moles of MEA (CO₂ absorbed) = 0.95 x 10.04 = 9.5 kmol

Remaining CO₂ = 0.54 kmol

4.5.3 MEA Solution Balance and Bottom Concentration of CO₂

Inert include gas components not being absorbed

Gas flow rate of inert (G_m) = 30.48 kmol/hr

Using CO₂ balance on Absorber

$$G_m (Y_b - Y_t) = L_m (X_b - X_t)$$

Here,

G_m = Molar Gas Flow Rate for inert

L_m = Molar Liquid Flow Rate for fresh MEA-solution

Y_b = Mole fraction of carbon dioxide in gas at the bottom

Y_t = Mole fraction of carbon dioxide in gas at the top

X_b = Mole fraction of carbon dioxide in liquid at the bottom

X_t = Mole fraction of carbon dioxide in liquid at the top

Now,

$$Y_b \text{ (kmol of CO}_2 \text{ at bottom / kmol of inerts)} = 10.04 / 30.481 = 0.329$$

$$Y_t \text{ (kmol of CO}_2 \text{ at the top / kmol of inerts)} = 0.54 / 30.481 = 0.017$$

Assuming a CO₂ free MEA solution is used for absorption

Therefore, top CO₂ in MEA-solution concentration, $X_t = 0$

Hence, we get

$$30.481 (0.329 - 0.017) = L_m * X_b,$$

$$L_m * X_b = 9.488 \text{ kmol/hr}$$

$$(L_m / G_m)_{\min} = \mathbf{0.508}$$

$$\text{Also } (L_m / G_m)_{\text{actual}} = (1.1 \text{ to } 1.5 \text{ times}) (L_m / G_m)_{\min}$$

Now assuming

$$(L_m / G_m)_{\text{actual}} = 1.25 * (L_m / G_m)_{\min}$$

$$(L_m / G_m)_{\text{actual}} = 1.25 * 0.508 = 0.6375$$

$$L_m = 0.6375 * 30.481 = \mathbf{19.431 \text{ Kmol/hr}}$$

But the amount obtained is only 14.5 MEA, thus the amount of solution is given by

$$\text{MEA} + \text{CO}_2 \text{ outlet} + \text{H}_2\text{S} + \text{water} = L_m = 19.431 / 0.145 = 134.01 \text{ kmol/hr}$$

$$X_b \text{ (CO}_2 \text{ in solution)} = 9.5 / 134.01 = 0.0701$$

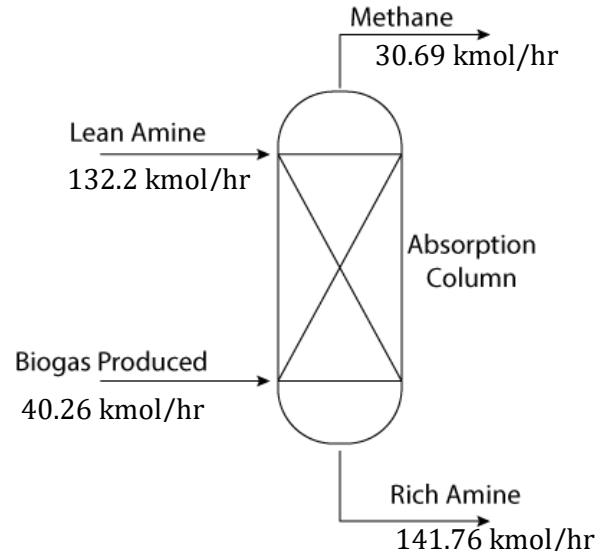


Figure 12 Illustration of Absorption Column

Table 16 Treated Biogas Composition

Gases	Composition	Mass Flow Rate (kg/hr)	Molar Flow Rate (kmol/hr)
<i>CH₄</i>	0.848	416.5	26.03
<i>CO₂</i>	0.016	22	0.5
<i>H₂S</i>	0.000031	0.034	0.001
<i>H₂O</i>	0.084	46.26	2.57
<i>N₂</i>	0.025	21.84	0.78
<i>O₂</i>	0.013	12.8	0.40
<i>H₂</i>	0.007	0.42	0.21
<i>NH₃</i>	0.007	3.4	0.2
Total	1	523.25	30.69

Table 17 Rich amine sol composition

Gases	Composition	Mass flow rate (kg/hr)	Molar flow rate (kmol/hr)
<i>H₂O</i>	0.797	2034.5	113.03
<i>H₂S</i>	0.00012	0.68	0.02
<i>CO₂</i>	0.067	419.76	9.54
MEA	0.135	1170.9	19.17
Total	1	3625.84	141.76

Table 18 Lean amine sol composition

Gases	Composition	Mass flow rate (kg/hr)	Molar flow rate (kmol/hr)
<i>H₂O</i>	0.85	2022.66	112.37
<i>H₂S</i>	0.000003	0.013	0.00039
<i>CO₂</i>	0.0015	8.36	0.19
MEA	0.14	1130.16	18.5
Total	1	3161.2	132.2

4.6 Material Balance on stripper

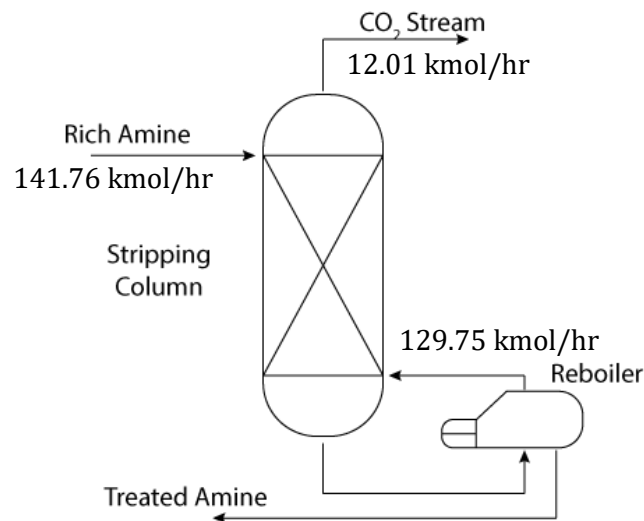


Figure 13 Illustration of Stripper

Assumptions:

1. 99% of CO₂ in Rich Amine is removed in CO₂ stream
2. 99% of H₂S in Rich Amine is removed along with CO₂ stream
3. 2% of MEA Solution in Rich Amine has been lost

⇒ For CO₂ stream

$$\begin{aligned}\text{CO}_2 &= 0.99 * (\text{Moles of CO}_2 \text{ in Rich Amine}) \\ &= 0.99 * (9.54) \\ &= 9.45 \text{ kmol/hr}\end{aligned}$$

$$\begin{aligned}\Rightarrow \text{H}_2\text{S} &= 0.99 * (\text{Moles of H}_2\text{S in Rich Amine}) \\ &= 0.99 * (0.02) \\ &= 0.019 \text{ kmol/hr}\end{aligned}$$

$$\begin{aligned} \Rightarrow \text{MEA} - \text{H}_2\text{O} &= 0.02 * (\text{Moles of MEA \& H}_2\text{O solution in Rich Amine}) \\ &= 0.02 * (19.17) + 0.02 (113.03) \\ &= 2.64 \text{ kmol/hr} \end{aligned}$$

$$\begin{aligned} \text{Total moles in CO}_2 \text{ Stream} &= 9.54 + 0.019 + 2.64 \\ &= 12.2 \text{ kmol/hr} \end{aligned}$$

$$\begin{aligned} \text{Total moles in Treated Amine Stream} &= 141.76 - 12.2 \\ &= 129.75 \text{ kmol/hr} \end{aligned}$$

Table 19 CO₂ Stream Composition

Gases	Composition	Mass flow rate (kg/hr)	Molar flow rate (kmol/hr)
H₂O	0.188	40.68	2.26
H₂S	0.00149	0.68	0.02
CO₂	0.78	411.4	9.35
MEA	0.031	23.94	0.38
Total	1	476.7	12.01

Table 20 Treated Amine Stream Composition

Gases	Composition	Mass flow rate (kg/hr)	Molar flow rate (kmol/hr)
H₂O	0.85	1984.86	110.77
H₂S	0.000003	0.012	0.00036
CO₂	0.0015	8.36	0.19
MEA	0.14	1183.7	18.79
Total	1	3176.14	129.75

4.7 Material Balance on Condensate Trap

Water Content in Biogas = 2.57 kmol/hr

Percentage of H₂O Removed = 95 %

Water content out = 2.57 - (2.57 * 0.95)
= 0.13 kmol/hr

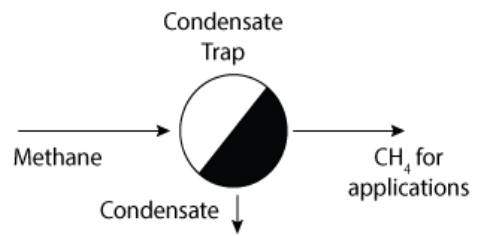


Figure 14 Illustration of Condensate Trap

Mass of Water after Condensate Trap = 2.34 kg

4.8 Final Bio Methane Composition

Table 21 Final Methane Composition

Gases	Composition	Mass Flow Rate (kg/hr)	Molar Flow Rate (kmol/hr)
CH₄	0.93	416.5	26.03
CO₂	0.017	22	0.5
H₂S	0.000031	0.034	0.001
H₂O	0.00046	2.34	0.13
N₂	0.025	21.84	0.78
O₂	0.013	12.8	0.40
H₂	0.008	0.42	0.21
NH₃	0.007	3.4	0.2
Total	1	524.25	28.34

ENERGY BALANCE

Basis: 1 hour

Reference Temperature: 25°C

5.1 Energy Balance on Mixer

Stream coming from storage tank

Temperature of feed = 25°C

Pressure of feed = 1bar

Table 22 Stream Composition Mixer

Component	Mass flowrate (kg/hr)	C _p (kJ/kg.K)
Wastewater	24050.8	3.98
TSS	1086.12	3.81
Total	25136.9	

Average C_p = 3.97 kJ/kg.K

Stream of manure added

Temperature = 25°C

Pressure = 1bar

Table 23 Manure Stream Composition

Component	Mass flowrate (kg/hr)
Water content	1,667
TSS	133.34
VSS	109.33 (.82 * TSS)
Total	1800.34

Average $C_p = 3.2 \text{ kJ/kg.K}$

Out stream of Mixer

Temperature = 35°C

Pressure = 1bar

Table 24 Mixer out stream

Component	Mass flowrate (kg/hr)	C_p (kJ/kg.K)
Water Content	25717.8	3.98
TSS	1219.45	3.81
VSS	1000 (.82 * TSS)	
Total	26937.25	

Average $C_p = 3.97 \text{ kJ/kg.K}$

Using formula

$$\begin{aligned} Q &= m C_p \Delta T \\ &= 26937.25 * 3.97 * (35 - 25) \\ &= 1069408.825 \text{ kJ/hr} \end{aligned}$$

Energy Required in mixer is 297.06 KW.

5.2 Energy Balance on Digester

Stream coming from mixer

Temperature = 35°C

Pressure = 1bar

Table 25 Waste in Digester

Component	Mass flowrate (kg/hr)	C _p (kJ/kg.K)
Water Content	25717.8	3.98
TSS	1219.45	3.81
VSS	1000 (.82*TSS)	
Total	26937.25	

Average C_p = 3.97 kJ/kg.K

Using formula

$$\begin{aligned}
 Q &= m C_p \Delta T \\
 &= 26937.25 * 3.97 * (35 - 25) \\
 &= 1069408.825 \text{ kJ/hr}
 \end{aligned}$$

Table 26 Series of Reactions in Digester

Component	Reactions	Energy Yield (kJ/mol CH ₄)
Hydrogen	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	131
Formic Acid	$4COOH \rightarrow CH_4 + 3CO_2 + 2H_2O$	145
Methanol	$4CH_3OH \rightarrow 3CH_4 + CO_2 + H_2O$	105
Acetic Acid	$CH_3COOH \rightarrow CH_4 + CO_2$	36

Digester reactions and energy yield

Avg Energy Yield = 104.25 kJ/mol CH₄

Energy Yield in Digester = 2713.68 kJ/mol CH₄

Moles = 26.04 kmol

Average C_p of Biogas = 1.962 kJ/kg.K

$$\text{Mass flow rate} = 954 \text{ kg/hr}$$

$$\text{Using } Q = m C_p \Delta T$$

ΔT would be approximately equals to 38 K

So, the gas will leave at 321 K

$$\begin{aligned} Q &= m C_p \Delta T \\ &= 954 * 1.962 * 23 \\ &= 43050.204 \text{ kJ/hr} \end{aligned}$$

Water leaving from top of digester

$$\text{Mass flowrate} = 25530.2 \text{ kg/hr}$$

$$\text{Cp of water} = 3.98 \text{ kJ/kg.K}$$

$$\Delta T = 23 \text{ K}$$

$$\begin{aligned} Q &= m C_p \Delta T \\ &= 25530.2 * 3.98 * 23 \\ &= 2337034.5 \text{ kJ/hr} \end{aligned}$$

$$E_{\text{net}} = E_{\text{in}} - E_{\text{out}}$$

$$= 1069408.825 - (43050.204 + 2337034.5)$$

$$= -1310675.87 \text{ kJ/hr}$$

Hence the reaction in digester is exothermic.

5.3 Energy Balance on Absorber

Biogas entering at

Temperature = 48°C

Pressure = 1.66 bar

Table 27 Biogas to Absorber Composition

Gases	Composition	Mass flowrate (kg/hr)	Molar flowrate (kmol/hr)	Cp (kJ/kg.K)
CH₄	0.65	416.5	26.04	2.34
CO₂	0.25	441.7	10.04	0.844
H₂S	0.0005	0.68	0.02	0.92
H₂O	0.06	57.43	2.57	4.18
N₂	0.0195	21.82	0.78	1.04
O₂	0.01	12.77	0.40	0.919
H₂	0.005	0.427	0.21	14.32
NH₃	0.005	3.44	0.20	2.19
Total	100	954.77	40.26	

Average Cp = 2.51 kJ/kg.K

$$Q_1 = m \text{ Cp } \Delta T$$

$$= 954.77 * 2.51 * 23 = 55118.87 \text{ kJ/hr}$$

Fresh amine entering absorber

Temperature = 40°C

Pressure = 1 bar

Table 28 Lean Amine composition to Absorber

Component	Composition	Mass flowrate (kg/hr)	Cp (kJ/kg.K)
Water	0.84	2026.23	4.18
MEA	0.16	1357.7	2.78
Total	1	3384.93	

Average Cp = 3.96 kJ/kg.K

$$\begin{aligned}
 Q_2 &= m C_p \Delta T \\
 &= 3384.93 * 3.96 * 15 \\
 &= 201005.42 \text{ kJ/hr}
 \end{aligned}$$

Methane leaving from top of absorber

Temperature = 49°C

Pressure = 1.66 bar

Table 29 Methane composition from Absorber

Gases	Composition	Mass flowrate (kg/hr)	Molar flowrate (kmol/hr)	Cp (kJ/kg.K)
CH₄	0.848	416.5	26.03	2.34
CO₂	0.016	22	0.5	0.844
H₂S	0.000031	0.034	0.001	0.92
H₂O	0.084	46.26	2.57	4.18
N₂	0.025	21.84	0.78	1.04
O₂	0.013	12.8	0.40	0.919
H₂	0.007	0.42	0.21	14.32
NH₃	0.007	3.4	0.2	2.19
Total	100	523.25	30.69	

$$\text{Average } C_p = 2.51 \text{ kJ/kg.K}$$

$$\begin{aligned} Q_3 &= m C_p \Delta T \\ &= 523.25 * 2.51 * 24 \\ &= 31535.64 \text{ kJ/hr} \end{aligned}$$

Rich Amine solution leaving from bottom of absorber

Temperature = 70°C

Pressure = 1.66 bar

Table 30 Rich Amine leaving Composition

Component	Composition	Mass flowrate (kg/hr)	C _p (kJ/kg.K)
H₂O	0.797	2034.54	4.18
H₂S	0.00012	0.68	1.01
CO₂	0.067	419.76	0.88
MEA	0.135	1207.7	2.92
Total	1	3662.63	

$$\text{Average } C_p = 3.78 \text{ kJ/kg.K}$$

$$\begin{aligned} Q_4 &= m C_p \Delta T \\ &= 3662.63 * 3.78 * 45 \\ &= 623013.363 \text{ kJ/hr} \end{aligned}$$

$$E_{\text{net}} = E_{\text{in}} - E_{\text{out}}$$

$$\begin{aligned} E_{\text{net}} &= (55118.87 + 201005.42) - (623013.363 + 31535.64) \\ &= -398424 \text{ kJ/hr} \end{aligned}$$

Hence, the process in absorption column is exothermic.

5.4 Energy Balance on Stripper

Rich amine solution coming from heat exchanger

Temperature = 132°C

Pressure = 1.66 bar

Table 31 Feed to stripper

Component	Composition	Mass flowrate (kg/hr)	Cp (kJ/kg.K)
H₂O	0.797	2034.54	4.18
H₂S	0.00012	0.68	1.01
CO₂	0.067	419.76	0.88
MEA	0.135	1207.7	2.92
Total	1	3662.63	

Average Cp = 3.78 kJ/kg.K

$$Q_1 = m C_p \Delta T = 3662.63 * 3.78 * 107 = 14816433.53 \text{ kJ/hr}$$

Carbon Dioxide stream leaving from top of stripper column

Temperature = 115 °C

Pressure = 1.26 bar

Table 32 CO₂ Stream Out of Stripper

Component	Composition	Mass flowrate (kg/hr)	Cp (kJ/kg.K)
H₂O	0.188	40.68	4.19
H₂S	0.00149	0.68	1.08
CO₂	0.78	411.4	0.926
MEA	0.031	23.9	2.983
Total	1	476.7	

Average Cp = 1.6 kJ/kg.K

$$\begin{aligned}
 Q_2 &= m C_p \Delta T \\
 &= 476.7 * 1.6 * 90 \\
 &= 68644.8 \text{ kJ/hr}
 \end{aligned}$$

Lean amine solution leaving from stripper column

Temperature = 152°C

Pressure = 1.26 bar

Table 33 Amine Leaving the stripper Composition

Component	Composition	Mass flowrate (kg/hr)	Cp (kJ/kg.K)
H₂O	0.85	1993.8	4.19
H₂S	0.000003	0.012	1.08
CO₂	0.0015	8.36	0.926
MEA	0.14	1183.7	2.983
Total	1	3185.9	

$$\text{Average } C_p = 3.98 \text{ kJ/kg.K}$$

$$\begin{aligned}
 Q_3 &= m C_p \Delta T \\
 &= 3185.9 * 3.98 * 127 \\
 &= 1610345.01 \text{ kJ/hr}
 \end{aligned}$$

$$E_{\text{net}} = E_{\text{in}} - E_{\text{out}}$$

$$\begin{aligned}
 E_{\text{net}} &= (14816433.53) - (68644.8 + 1610345.01) \\
 &= 13137443.71 \text{ kJ/hr}
 \end{aligned}$$

5.5 Energy through Reboiler

$$Q_B = Q_{\text{lean amine}} + Q_{\text{stream from reboiler}}$$

$$= 1179229.02 \text{ kJ/hr} + (m_{\text{water}} \lambda_{\text{water}} + m_{\text{MEA}} \lambda_{\text{MEA}})$$

$$\lambda_{\text{water}} = 2258 \text{ kJ/kg}$$

$$\lambda_{\text{MEA}} = 837 \text{ kJ/kg}$$

$$= 1179229.02 + (60.28 * 2258 + 33.6 * 837)$$

$$= 1316993.82 \text{ kJ/hr}$$

5.6 Condensate Trap

For H₂O removal

$$Q = m C_p \Delta T$$

∴ m = mass flowrate of water in methane

stream

$$= 46.26 * 4.18 * 24$$

$$= 4640.8 \text{ kJ/hr}$$

DESIGNING & EQUIPMENT SIZING

6.1 Conveyer Belt

General formula for capacity:

$$\text{Capacity (kg/s)} = \text{Load cross-section area (m}^2\text{)} * \text{belt speed (m/s)} * \text{material density (kg/m}^3\text{)}$$

$$\text{Belt speed} = 60 \text{ ft/min} = 0.305 \text{ m/s}$$

Table 34 Dimensions of Belt

Dimensions of Conveyer Belt	
Length	1.52 m
Width	0.33 m

Dimensions of Conveyer Belt

$$\text{Cross Section Area} = \text{length} * \text{width}$$

$$= 0.33 * 1.52$$

$$= 0.5 \text{ m}^2$$

$$\text{Capacity} = 70.4 \text{ kg/s}$$

To off load 25,136 kg/hr of Waste Sludge to Mixer.

$$\text{Total Belts to be employed} = 1$$

6.2 Mixer

Unit made up of a flat circular bottom with cylinder and conical top

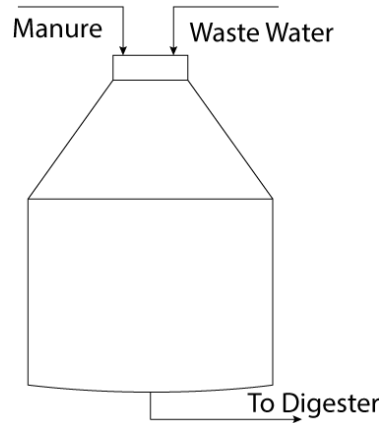


Figure 15 Illustration of Mixer

$$\text{Total Volume of Mixer Unit} = \pi r^2 h + \pi r^2 \frac{h}{3}$$

Assuming D: H ratio = 1:2

$$D = 2r$$

$$h = 4r$$

$$V_m = 4\pi r^3 + \frac{4}{3}\pi r^3 = 5.33\pi r^3$$

$$r = \sqrt[3]{\frac{27.52}{5.33\pi}} = 1.18 \text{ m}$$

$$D = 2.36 \text{ m}$$

$$h = 4.72 \text{ m}$$

Total Volume of Mixer (Water + Manure + 10%
Safety Factor)

$$\text{Volume of waste Water + Manure} = 25.02 \text{ m}^3$$

$$\text{Safety Factor} = 0.1 * 25.02 = 2.50$$

$$\text{Total Volume Mixer} = 27.52 \text{ m}^3$$

Vessel is equipped with **3 internal impellers**

Diameter of Impellers, $T = 0.42 * D = 0.99$

Distance Separating impellers = $0.375 * D = 0.88$ m

Bottom off clearance of the lowest impeller = 0.42 m

Relative impeller rotation = 45°

Impeller rotation = 37 rpm

No. of Baffles = 4

Baffle width = $1/12 * D = 0.20$ m

6.3 UASB Digester

New VSS produced as a result of BOD removal, the yield coefficient assumed as 0.1 g VSS/g BOD removed.

New VSS produced in BOD Removal, (mg/L) =

$$\left\{ \begin{array}{l} \text{Influent BOD, (mg/L)} * \text{BOD} \\ \text{Removal (\%)} * \text{Yield Coefficient, (g} \\ \text{VSS/g BOD Removed)} \end{array} \right\}$$

Influent BOD = 300 mg/L

BOD Removal % = 0.9

Yield Coefficient = 0.1

New VSS = 27 mg/L

Non-degradable residue, (mg/L) = VSS, (mg/L) *

(1- degradable fraction)

Degradable Function = 0.9

Non-degradable residue, (mg/L) = 27 mg/L

S. No	Parameters	Assumptions	Ref.
1.	Solid retention time	40 days	[6]
2.	Temperature of reactor	20° - 32° C	[4]
3.	BOD removal yield coefficient	0.1 g VSS /g BOD _{removed}	[2]
4.	Degradable residues of VSS coming in the inflow	90%	[6]
5.	COD removal efficiency	80 %	[6]
6.	Reactor height	4 – 5.9 m	[2]
7.	Average concentration of sludge in blanket	75 %	[2]
8.	Effective depth of sludge blanket	2.2 m	[2]
9.	Theoretical CH ₄ , m ³ / kg COD removed	0.35 m ³	[2]

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New Ash received in the inflow, (mg/L) = TSS, (mg/L) – VSS, (mg/L) = 75 mg/L

$$\text{Total sludge produced, (kg/day)} = \left\{ \begin{array}{l} \text{New VSS produced in BOD removal,} \\ \text{(mg/L) + Non - degradable residue,} \\ \text{(mg/L) + Ash received in the inflow,} \\ \text{(mg/L)} \end{array} \right\}$$

Sludge Produced = 104.7 kg/day

6.3.1 Solid Retention Time

$$\text{Solid Retention Time (SRT)} = \frac{\text{Total quantity of sludge present in the reactor, (kg)}}{\text{Quantity of sludge removed per day, (kg/day)}}$$

Quantity Sludge Removed = 1219 kg

$$\text{SRT} = 13.2$$

Assumptions:
HRT = 14hr
Up Flow Velocity = 0.6 m/hr
No. of Digesters = 3

6.3.2 Digester Height

Digester Height = Up Flow Velocity * HRT

$$\text{Height} = 8.4 \text{ m}$$

6.3.3 Area of one Digester

$$\text{Area (m}^2\text{)} = \frac{\text{Flow Rate (m}^3\text{/hr)}}{\text{Up Flow Velocity (m/hr)}}$$

$$\text{Area} = 12.2 \text{ m}^2$$

6.3.4 Diameter of one Digester

$$\text{Diameter (m)} = \sqrt[2]{\text{Area} * \frac{4}{\pi}}$$

$$\text{Diameter} = 3.94 \text{ m}$$

$$\text{Radius} = 1.97 \text{ m}$$

6.3.5 Volume of Digester

$$\text{Volume (m}^3\text{)} = \pi r^2 h$$

$$\text{Volume} = 95.2 \text{ m}^3$$

6.4 Packed Bed Absorber

MEA Required

$$\text{Moles of MEA} = 18.5 \text{ kmol/hr}$$

$$\text{Mass of MEA} = 1165 \text{ kg/hr}$$

Water Requirement

84 % Water

$$\text{Moles of Water} = 112.27 \text{ kmol/hr}$$

$$\text{Mass of Water} = 2020.8 \text{ kg/hr}$$

Gas & Liquid Properties

$$\text{Gas flow rate (G}_m\text{)} = 40.08 \text{ kmol/hr}$$

$$\text{Density of gas } (\rho_m) = 0.984 \text{ kg/m}^3$$

$$\text{Liquid Flow Rate (L}_m\text{)} = 132.2 \text{ kmol/hr}$$

$$\text{Liquid Density } (\rho_L) = 1034 \text{ kg/m}^3$$

$$\text{Liquid Viscosity } (\mu) = 0.0053 \text{ kg/m.s}$$

$$G_m (y_1 - y_2) = L_m (x_2 - x_1)$$

$$y_1 = 0.25$$

Operating Conditions

$$\text{Temperature} = 40 \text{ }^\circ\text{C}$$

$$\text{Pressure} = 1.66 \text{ bar}$$

$$\text{Efficiency} = 95 \%$$

$$y_2 = 0.016$$

$$x_1 = 0$$

$x_2 =$ to be calculated using above equation

$$x_2 = 0.07$$

6.4.1 Slope Calculation

$$m = \frac{y_1}{x_1}$$

$$\frac{y_1}{y_2} = 15.07$$

$$\frac{mG_m}{L_m} = 1.07$$

From appendix Figure 2

$$\text{NOG} = 6.8$$

6.4.2 Packing Properties

Raschig Rings (Ceramic)

From appendix Figure 1

Diameter of Packing = 51 mm

Bulk Density = ρ = 651 kg/m³

Surface Area = a = 95 m²/m³

Packing Factor = F_p = 210 m⁻¹

Packing Factor = F_p = 64.02 ft⁻¹

6.4.3 Flow Factor Calculation

$$F_{LV} = \frac{L}{V} \sqrt{\frac{\rho_v}{\rho_l}}$$

$$F_{LV} = 0.102$$

Percentage Flooding

$$\text{Percentage Flooding} = \sqrt{\frac{K_4}{K_4^*}} * 100$$

Usually, the pressure drop assumed in the absorber is 15-50 mm of water per meter of packing

Using Appendix Figure 3

$$K_4 = 1.8$$

$$K_4^* = 5.4$$

$$\text{Percentage Flooding} = 57.73$$

6.4.4 Gas Mass Velocity Calculation:

$$V_w^* = \sqrt{\frac{K_4 \rho_v (\rho_l - \rho_v)}{13.1 F_p \left(\frac{\mu_l}{\rho_l}\right)^{0.1}}}$$

$$V_w^* = 0.634$$

6.4.5 Column Diameter

$$\text{Column Area (m}^2\text{)} = \frac{G}{V_w^*}$$

$$\text{Column Area} = 0.94 \text{ m}^2$$

$$\text{Column Diameter} = D_c = \sqrt{\frac{4 * \text{Area}}{\pi}}$$

Diameter = 1.09 m

6.4.6 Channeling

To check whether the conditions to minimize channeling are satisfied or not, take ratio

$$\text{Channeling} = \frac{D_c}{D_p}$$

$$\text{Channeling} = 21.54$$

As it is greater than 8 so,

There would be no channeling at all.

6.4.7 Height of Absorption Column

Height of Transfer Unit (HOG)

$$H_{OG} = H_G + m \frac{G_m}{L_m} H_L$$

From Appendix Figure 4 & Figure 5

$$H_g = 0.18 \text{ m}$$

$$H_L = 0.62 \text{ m}$$

$$HOG = 0.67 \text{ m}$$

Height of Absorption Column

$$Z = N_{OG} \times H_{OG}$$

$$Z = 4.57 \text{ m}$$

Height of Packing = 4.57 m

Allowances for liquid distribution = 0.5 m

Allowances for liquid redistribution = 0.5 m

Height of Column = 5.57 m

6.4.8 Pressure Drop Calculation

$$\Delta P_{flooding} = 0.115(F_P)^{0.7}$$

Pressure Drop = 2.114 (in. of H₂O / ft. of Packing)

6.5 Stripper

Table 35 Stripper design parameters

Parameters	Values
Gas Flow Rate (kmol/hr)	12.01
Liquid Flow Rate (kmol/hr)	141.76
Henry's Constant	2700
S= HG/L	228.75
X _{in}	0.067
X _{out}	0.0015
P (atm)	1.26
T (°C)	152

6.5.1 Height Calculations

Height of Tower = NTU * HETP

$$NTU = \left(\frac{S}{S-1}\right) * \ln \left[\left(\left(1 - \frac{1}{S}\right) * \left(\frac{X_{in}}{X_{out}}\right) \right) + \frac{1}{S} \right]$$

$$= 1.04 * \ln [(0.979 * 44.67) + 0.0403]$$

$$NTU = 3.94$$

$$\ln HETP = n - 0.187 * \ln(st) + 0.213 * \ln \mu$$

Surface Tension = 63.3 dyne/cm

$$\mu = 1.54 \text{ cp}$$

$$n = 1.4$$

$$\ln \text{ HETP} = 0.536$$

$$\text{HETP} = 1.7 \text{ ft}$$

$$= 0.52 \text{ m}$$

$$\text{Height of Tower} = 3.94 * 0.52$$

Height = 2.14 m

6.5.2 Diameter Calculation

Table 36 Stripper Diameter Parameters

Parameter	Values
Liquid Mass (kg)	3662.7
Gas Mass (kg)	476.7
Liquid Flow Rate (kg/s)	1.01
Gas Flow Rate (kg/s)	0.13
ρ_{liq} (kg/m ³)	989.2
ρ_{gas} (kg/m ³)	1.6

$$\frac{L}{G} * \left(\frac{\rho_{gas}}{\rho_{liq}} \right)^{0.5} = 0.28$$

Using Appendix Figure 14

$$\text{Capacity factor} = 0.3$$

Now using formula

$$(G^2 * F * \varphi \mu^{0.2} / \rho_g \rho_l g_c) = 0.3$$

Berl saddle (ceramic) 1-inch packing

Packing factor,

$$F = 110$$

$$G' = 1.45$$

$$\text{Area} = \frac{G}{G'}$$

$$A = 0.79 \text{ m}^2$$

$$\text{Radius} = \sqrt{\frac{\text{Area}}{\pi}}$$

$$\text{Radius} = 0.504 \text{ m}$$

$$\text{Diameter} = 2r$$

Diameter = 1.009 m

6.6 Design of Heat Exchanger

❖ Shell side

Mass flowrate of lean amine solution = 0.88 kg/s

Temperature inlet = T_1 = 152°C

Temperature Outlet = T_2 = 82°C

Cp of solution = 3.9 kJ/kg.K

Density = 961 kg/m³

Thermal conductivity = 0.786 W/m.K

Viscosity = 0.00735 Pa.s

Specific Gravity = 0.784

❖ **Tube side**

Mass flowrate of rich amine solution	= 1.02 kg/s
Temperature inlet = t_1	= 70°C
Temperature Outlet = t_2	= 132°C
Cp of solution	= 3.2 kJ/kg.K
Density	= 955 kg/m ³
Thermal conductivity	= 0.91 W/m.K
Viscosity	= 0.00865 Pa.s
Specific Gravity	= 0.098

Table 37 Formulae Sheet for Heat Exchanger

Specifications	Formula
Heat Balance	$Q = mC_p\Delta T$
LMTD	$(\Delta T_2 - \Delta T_1) / \ln\left(\frac{\Delta T_2}{\Delta T_1}\right)$
Flow Area	Shell Side $a_s = ID * \frac{C'_B}{144P_T}$, Tube Side $a_t = \frac{N_t a'_t}{144n}$
Mass Velocity	Shell Side $G_s = \frac{W}{a_s}$, Tube Side $G_t = \frac{W}{a_t}$
Reynold's Number	Shell Side $Re_{e,s} = \frac{D_e G_s}{\mu}$, Tube Side $Re_{e,t} = \frac{D G_t}{\mu}$
Design Overall Co-efficient	$U_D = \frac{Q}{A * LMTD}$
Baffle Spacing	0.5 * Shell ID
No of Baffles	$\frac{\text{Length of Tube}}{\text{Baffle Spacing}}$
Shell Side Pressure Drop	$\Delta P_s = \frac{f G_s^2 D_s (N + 1)}{5.22 * 10^{10} D_{e,s}}$
Tube Side Pressure Drop	$\Delta P_t = \frac{f G_t^2 L n}{5.22 * 10^{10} D_s}$

Specifications from the appendix Figure 9

❖ Shell side

Inner diameter = 17.25 in

Baffle Spaces = 5 in

Passes = 1

❖ Tube side

Number of tubes = 112

Length = 20 ft

Outer diameter = 1 in

Schedule no. = 40

Pitch = 1.25 in

Passes = 2

Inner diameter = 0.81 in

Clearance = Pitch - Outer diameter

$$= 1.25 - 1 = 0.25 \text{ in}$$

6.6.1 LMTD calculation,

Temperature	Shell side	Tube side	Difference
High Temperature (°C)	152	132	20
Low Temperature (°C)	82	70	12

LMTD = 15.66 °C

As, there are 2 passes on tube side so we have to find corrected LMTD using the values of R and S

$$R = \frac{T_1 - T_2}{t_2 - t_1} = 1.129$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} = 0.756$$

Now we will find value of correction factor using values of R and S in appendix

Correction factor = $F_t = 1$

Corrected LMTD = 15.66°C

❖ Heat duty

$$Q = m C_p \Delta T$$

$$Q_{\text{duty}} = 637426.8 \text{ kJ/hr}$$

6.6.2 Heat transfer coefficient for shell side

$$\text{Equivalent diameter} = D_e = 0.99 \text{ in} \quad (\text{from appendix Figure 15})$$

$$\text{Flow area shell} = 0.11979 \text{ ft}^2 = 0.0110 \text{ m}^2$$

$$\text{Mass Velocity} = \frac{0.88}{0.0110} = 79.848 \text{ kg/m}^2\text{-s}$$

$$G_s = 58875.37 \text{ lb/ft}^2\text{-hr}$$

$$R_{e,s} = \frac{D_e G_s}{\mu} = 2.60\text{E}+03$$

From Appendix we have calculated JH factor

$$JH = 78$$

Using Formula

$$h_o = \frac{JH}{D_e} * k^{\frac{2}{3}} * (C_p * \mu)^{\frac{1}{3}}$$

$$h_o = 3721.40 \text{ W/m}^2\text{K}$$

6.6.3 Heat transfer coefficient for tube side

From Appendix Figure 16

Flow area per tube = 0.515 in

Total Flow area of tube is given by

$$a_t = \frac{N_t a'_t}{n}$$

$$a_t = 0.016889$$

$$\text{Mass Velocity} = G_t = \frac{1.02}{0.01689} = 60.39 \text{ kg/m}^2\text{-s}$$

$$G_t = 44528.65 \text{ lb/ft}^2\text{-hr}$$

$$\text{Reynold Number} = \text{Re} = \frac{D \times W_t}{\mu \times a_t}$$

$$\text{Re} = 1.37\text{E}+03$$

Using graph for tube side we get JH factor as follow

$$\text{JH} = 40$$

$$h_i = \frac{\text{JH}}{D} \times K^{\frac{2}{3}} \times (C_p \times \mu)^{\frac{1}{3}}$$

Using this formula

$$h_i = 2730.22 \text{ W/m}^2 \text{ K}$$

$$h_{io} = h_i * \frac{\text{ID of tube}}{\text{OD of tube}}$$

$$h_{io} = 2211.48 \text{ W/m}^2 \text{ K}$$

6.6.4 Calculation of clean coefficient

$$\frac{1}{U_c} = \frac{1}{h_{io}} + \frac{1}{h_o}$$

$$U_c = 1387.15 \text{ W/m}^2 \text{ K}$$

From Appendix Figure 16

Surface area to length ratio = 0.281 ft²/ft

Surface area to length ratio = 0.289 m²/m

Area = 0.289 * 112 * 20 = 629.44 ft²

Area = 58.50 m²

Design coefficient = $U_D = \frac{Q}{A \times \Delta t}$

$$U_D = 695.674 \text{ W/m}^2 \text{ K}$$

Dirt Factor = $R_d = \frac{1387.15 - 695.674}{1387.15 * 695.674}$

= 0.000716

As value of R is less than 0.002 so design is acceptable.

6.6.6 Pressure Drop Calculation

⇒ **Pressure Drop in shell side**

Using Reynold number for shell side from graph

Friction factor= $f = 0.002$

Number of crosses are given as

$$N+1 = \frac{L}{B} = 48$$

$$\Delta P_s = \frac{f G_s^2 D_s (N + 1)}{5.22 * 10^{10} D_e S}$$

$$\Delta P_s = 0.8500 \text{ psi}$$

⇒ **Pressure Drop in tube side**

Using Reynold number for tube side

$$\text{Friction Factor} = f = 0.01296$$

$$\Delta P_t = \frac{f G_t^2 L n}{5.22 * 10^{10} D_s}$$

$$\Delta P_t = 0.4593 \text{ psi}$$

$$\text{Pressure Drop due to fittings in tube} = \Delta P_t = \frac{4n}{s} \times \frac{V^2}{2g}$$

Velocity Head from Graph

$$\frac{V^2}{2g} = 0.018$$

$$\Delta P_t = 1.469 \text{ psi}$$

$$\text{Total Pressure Drop} = 1.9287 \text{ psi}$$

As the pressure drop on Tube side is less than 10 psi so the Design is suitable.

6.7 Design of MEA cooler

❖ Shell side

$$\text{Mass flowrate of Water} = 1.34 \text{ kg/s}$$

$$\text{Temperature inlet} = T_1 = 25^\circ\text{C}$$

$$\text{Temperature Outlet} = T_2 = 50^\circ\text{C}$$

$$\text{Cp of solution} = 4.2 \text{ kJ/kg.K}$$

$$\text{Density} = 1000 \text{ kg/m}^3$$

$$\text{Thermal conductivity} = 0.598 \text{ W/m.K}$$

Viscosity = 0.001 Pa.s

Specific Gravity = 1

❖ **Tube side**

Mass flowrate of lean amine solution = 1.02 kg/s

Temperature inlet = t_1 = 82°C

Temperature Outlet = t_2 = 40°C

Cp of solution = 3.9 kJ/kg.K

Density = 955 kg/m³

Thermal conductivity = 0.785 W/m.K

Viscosity = 0.00735 Pa.s

Specific Gravity = 0.784

Specifications from the appendix

⇒ Shell side

Inner diameter = 15.25 in

Baffle Spaces = 5 in

Passes = 1

⇒ Tube side

Number of tubes = 76

Length = 20 ft

Outer diameter = 1 in

Schedule no. = 40

Pitch = 1.25 in

Passes = 2

Inner diameter = 0.81 in

Clearance = Pitch – Outer diameter

= 1.25 – 1 = 0.25 in

6.7.1 LMTD calculation

Temperature	Shell side	Tube side	Difference
High Temperature (°C)	50	82	32
Low Temperature (°C)	25	40	15

$$\text{LMTD} = 22.42 \text{ } ^\circ\text{C}$$

As there are 2 passes on tube side so we have to find corrected LMTD using the values of R and S

$$R = \frac{T_1 - T_2}{t_2 - t_1} = 0.595$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} = 0.736$$

Now we will find value of correction factor using values of R and S in appendix

Correction factor = $F_t = 0.87$

Corrected LMTD = 19.51°C

❖ Heat duty

$$Q = m C_p \Delta T$$

$$Q_{\text{duty}} = 140755.1 \text{ kJ/hr}$$

6.7.2 Heat transfer coefficient for shell side

Equivalent diameter = $D_e = 0.99 \text{ in}$ (from appendix Figure 15)

Flow area shell = 0.11979 ft² = 0.0110 m²

$$\text{Mass Velocity} = \frac{1.34}{0.0110} = 137.53 \text{ kg/m}^2\text{-s}$$

$$G_s = 101478.663 \text{ lb/ft}^2\text{-hr}$$

$$R_{e,s} = \frac{D_e G_s}{\mu} = 3.30\text{E}+03$$

From Appendix we have calculated JH factor

$$JH = 50$$

Using Formula

$$h_o = \frac{JH}{D_e} * k^{\frac{2}{3}} * (C_p * \mu)^{\frac{1}{3}}$$

$$h_o = 2331.71 \text{ W/m}^2\text{K}$$

6.7.3 Heat transfer coefficient for tube side

From Appendix Figure 16

Flow area per tube = 0.515 in

Total Flow area of tube is given by

$$a_t = \frac{N_t a'_t}{n}$$

$$a_t = 0.0114$$

$$\text{Mass Velocity} = G_t = \frac{1.02}{0.0114} = 80.99 \text{ kg/m}^2\text{-s}$$

$$G_t = 65621.18 \text{ lb/ft}^2\text{-hr}$$

$$\text{Reynold Number} = \text{Re} = \frac{D \times W_t}{\mu \times a_t}$$

$$\text{Re} = 2.37\text{E}+03$$

Using graph for tube side we get JH factor as follow

$$JH = 30$$

$$h_i = \frac{JH}{D} \times K^{\frac{2}{3}} \times (C_p \times \mu)^{\frac{1}{3}}$$

Using this formula

$$h_i = 3989.20 \text{ W/m}^2 \text{ K}$$

$$h_{io} = h_i * \frac{ID \text{ of tube}}{OD \text{ of tube}}$$

$$h_{io} = 3231.25 \text{ W/m}^2 \text{ K}$$

6.7.4 Calculation of clean coefficient

$$\frac{1}{U_c} = \frac{1}{h_{io}} + \frac{1}{h_o}$$

$$U_c = 1345.3 \text{ W/m}^2 \text{ K}$$

6.7.5 Design coefficient

From Graph Figure 16

$$\text{Surface area to length ratio} = 0.271 \text{ ft}^2/\text{ft}$$

$$\text{Surface area to length ratio} = 0.278 \text{ m}^2/\text{m}$$

$$\text{Area} = 0.289 * 112 * 20 = 411.92 \text{ ft}^2$$

$$\text{Area} = 38.28 \text{ m}^2$$

$$\text{Design coefficient} = U_D = \frac{q}{A \times \Delta t}$$

$$U_D = 188.3 \text{ W/m}^2 \text{ K}$$

$$\text{Dirt Factor} = R_d = \frac{1345.3 - 188.3}{1345.3 * 188.3}$$

$$= 0.00059$$

As value of R is less than 0.002 so design is acceptable.

6.6.6 Pressure Drop Calculation

⇒ Pressure Drop in shell side

Using Reynold number for shell side from graph

Friction factor= $f = 0.00098$

Number of crosses are given as

$$N+1 = \frac{L}{B} = 48$$

$$\Delta P_s = \frac{f G_s^2 D_s (N + 1)}{5.22 * 10^{10} D_e S}$$

$$\Delta P_s = 1.7130 \text{ psi}$$

⇒ Pressure Drop in tube side

Using Reynold number for tube side

Friction Factor = $f = 0.002$

$$\Delta P_t = \frac{f G_t^2 L n}{5.22 * 10^{10} D_s}$$

$$\Delta P_t = 0.1247 \text{ psi}$$

$$\text{Pressure Drop due to fittings in tube} = \Delta P_t = \frac{4n}{s} \times \frac{V^2}{2g}$$

Velocity Head from Graph

$$\frac{V^2}{2g} = 0.056$$

$$\Delta P_t = 0.5714 \text{ psi}$$

Total Pressure Drop = 0.6961 psi

As the pressure drop on Tube side is less than 10 psi so the Design is suitable.

SIMULATION

7.1 ASPEN PLUS

We have done our simulation on ASPEN PLUS. The reason of using ASPEN PLUS is that it has a model library where some typical chemical unit processes could be found. Besides, have a source with a large list of chemical compounds data for using it in the simulation. Otherwise, if special process or special chemical compound data is not found in, could be implemented in it. Using this software, the operating conditions of digestion, which depends on substrate degradation, biogas production kinetics and yield materials could be optimized.

Property package

- NRTL
- Sour SRK

The simulation of digestion process could be done by using NRTL and for removal of CO₂ from biogas in absorption column, we used Sour SRK.

7.2 Component list

- VFA (volatile fatty acids) represented by acetic acid, propionic acid, butyric acid and valeric acid.
- Long chain fatty acids represented by oleic acid.
- Glycerol
- Carbon hydrates represented by dextrose.
- All the main 20 amino acids without two exceptions Asparagine and Glutamine, for which Stickland reactions are not found. Therefore, their degradations are not known. So, their concentration will be supposed to be of the other amino acids proportionally. [Arginine, Histidine, Lysine, Tyrosine, Tryptophan, Phenylalanine,

Cysteine, Methionine, Threonine, Serine, Leucine, Isoleucine, Valine, Glutamic acid, Aspartic acid, Glycine, Alanine and Proline]. However, most of these amino acids are not well implemented in Aspen Plus databank because a lot of their thermodynamic data is missing. The solution is explained in the property method needed parameters section.

7.3 Reaction list

The Kinetic Reactions are added from the model as following the power law (however, temperature dependence is calculated separately), and kinetic constants are firstly supposed from excel calculation. All the kinetic reactions are supposed to follow first order kinetics.

Moreover, acid-base reactions are set as equilibrium reactions where non-information is needed to be filled apart from the stoichiometry due to Aspen Plus have all the data needed.

Afterwards of filling the compounds, the reactions can be implemented in the reaction chapter.

7.4 Flowsheet

Then the flowsheet is performed with every stream. Reactor is the core of the simulation as it represents the digester where all the chemical and biochemical reactions occur. CSTR (Continuous stirred tank reactor) is chosen as the reactor that is used in the real biogas plants. It needs strong calculations of the simulator. Total mixed flow and constant volume are assumed. Residence time is chosen as user defined parameter. The RCSTR model given by Aspen Plus have one source stream and one product stream, however, in a real plant the digester has two main product streams, one for the liquid phase, where are all the wastes, and another one for the

gaseous phase, where the biogas is collected, so real digester acts as a coupled RCSTR with FLASH separator (at the same conditions).

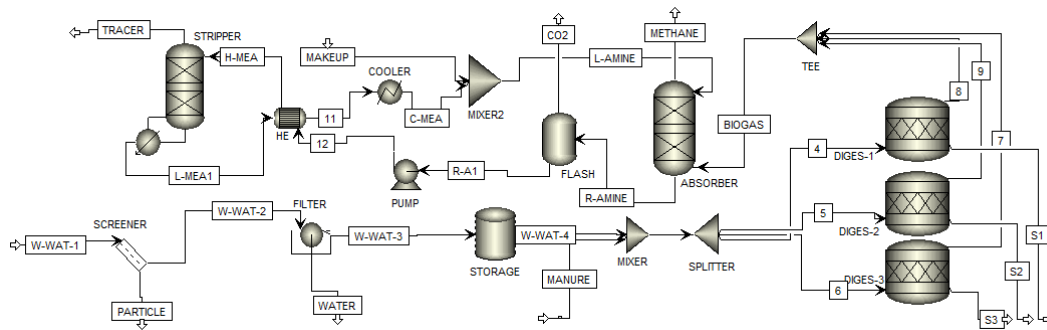


Figure 16 Flowsheet diagram on aspen plus

7.5 Operation

The digesters are assigned the reaction set and residence time is allocated for each digester. The parameters of temperature and pressure are applied according to mesophilic condition.

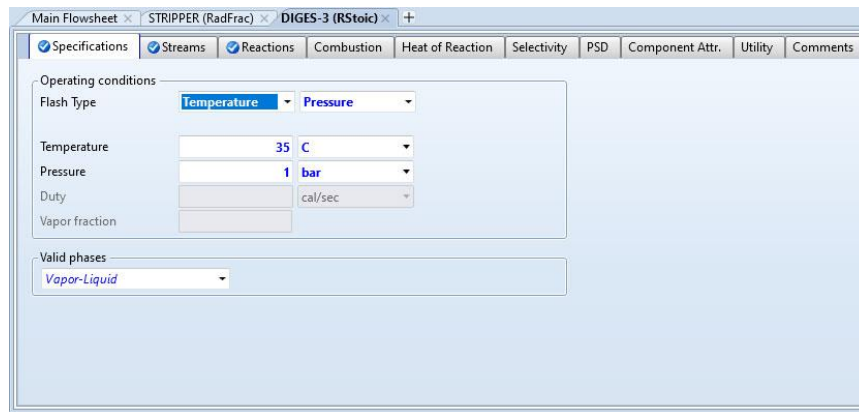


Figure 17 Parameters set in digester

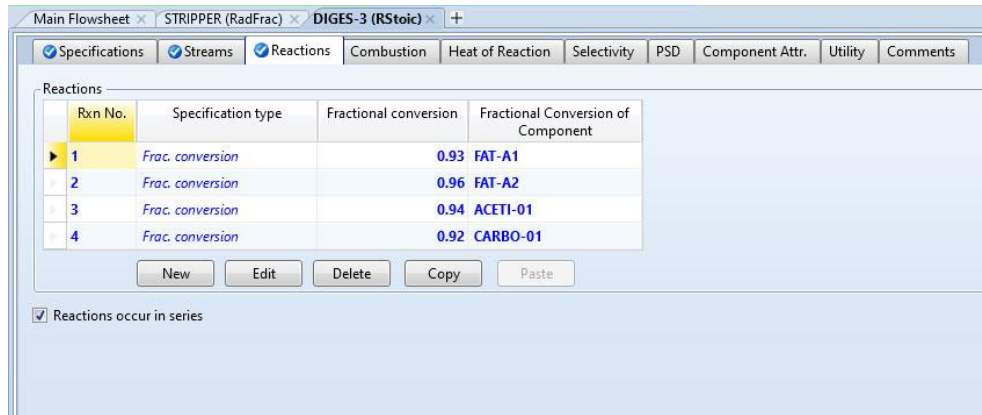


Figure 18 Reaction set in digester

After the reaction, the biogas is produced from the digester and its temperature, pressure and flowrate are noted.

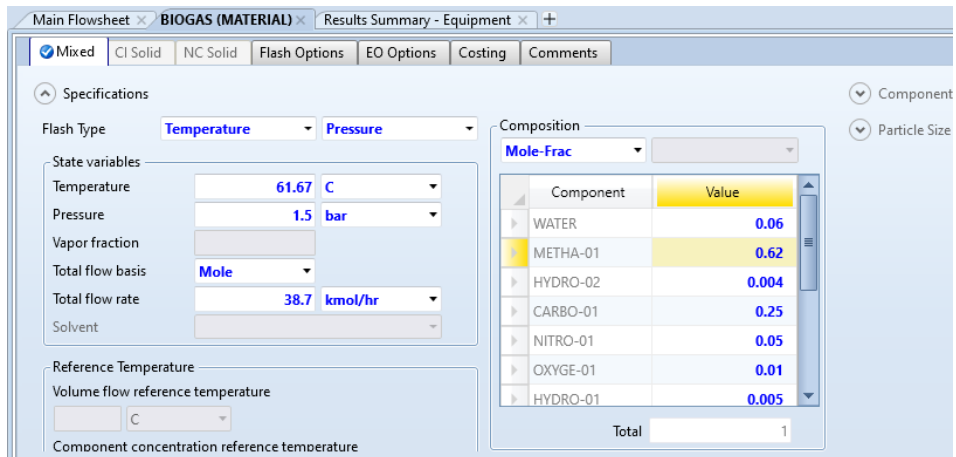


Figure 19 stream of biogas from digester

After leaving the digester, all the biogas streams enter the absorption column where CO₂ concentration is reduced using MEA solution and a stream of methane exits from top of column in which methane has 92% composition.

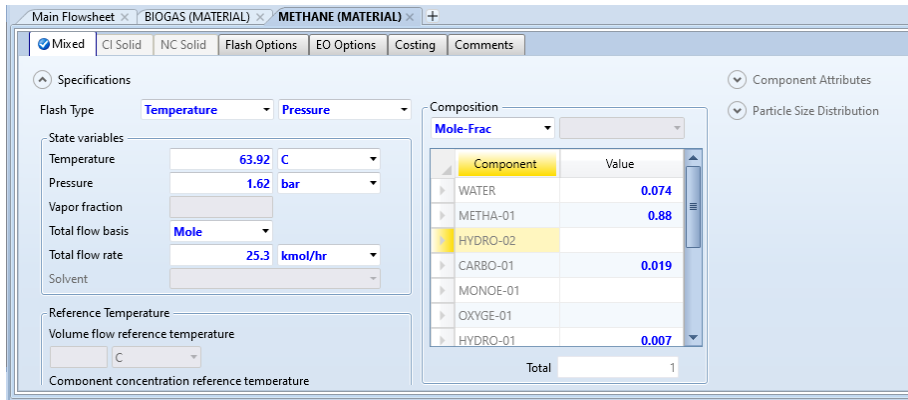


Figure 20 stream of methane from absorption column

The final flowsheet can be seen to analyze the streams flowrates, temperature and pressures. The values came from simulation are fluctuating from the calculated values because software uses its own methods.

Material	Heat	Load	Work	Vol.% Curves	Wt.% Curves	Petroleum	Polymers	Solids		
Units										
Description										
From			FILTER	SPLITTER	TEE	ABSORBER	ABSORBER	HE	STRIPPER	
To			SCREENER	STORAGE	DIGES-1	ABSORBER	FLASH	STRIPPER	HE	
Stream Class			CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	
Maximum Relative Error										
Cost Flow		\$/hr								
MIXED Substream										
Phase			Liquid Phase	Liquid Phase	Liquid Phase	Vapor Phase	Vapor Phase	Liquid Phase	Liquid Phase	Liquid Phase
Temperature		C	25	25	35	61.67	63.92	64.2	112.63	115.2
Pressure		bar	1	1	1	1.5	1.62	1.62	2.8	
Molar Vapor Fraction			0	0	0	1	1	0.05	0	
Molar Liquid Fraction			1	1	1	0	0	0.95	1	
Molar Solid Fraction			0	0	0	0	0	0	0	
Mass Vapor Fraction			0	0	0	1	1	0.043	0	
Mass Liquid Fraction			1	1	1	0	0	0.957	1	

Figure 21 Worksheet of Aspen Plus

ECONOMIC ANALYSIS

8.1 Costing

Costing is done using factorial method from chemical engineering design by Richardson and Coulson.

Total investment required = Fixed capital + working capital

Total operating cost = fixed cost + variable cost

For calculating fixed capital physical cost of equipment (PCE) is calculated initially

8.2 Cost Indexes:

Chemical plant cost indexes are dimensionless numbers employed to updating capital cost required to erect a chemical plant from past date to the later time, following changes in the value of money due to inflation and deflation.

8.3 Inflation:

It is a general increase in the prices of services and goods for an economy. When the price level rises each unit of currency buys fewer goods and services consequently.

8.4 Equipment cost

Using formula

$$C_e = C * S^n$$

Here,

C_e (\$) = purchased equipment cost

C = cost constant

(From Appendix)

S = characteristic size parameter

n = index for that type of equipment

- **Screener**

$$C_e = 680 \$ \quad \text{(Market Price)}$$

- **Conveyor**

$$\begin{aligned} C_e &= 1900 * 1.27^{0.75} \\ &= 2273.03 \$ \end{aligned}$$

- **Filter**

$$\begin{aligned} C_e &= 8800 * 15^{0.6} \\ &= 44682.5 \$ \end{aligned}$$

- **Storage tank**

$$\begin{aligned} C_e &= 2900 * 65^{0.6} \\ &= 35493.3 \$ \end{aligned}$$

- **Mixer**

$$\begin{aligned} C_e &= 2800 * 56^{0.4} \\ &= 140098.4 \$ \end{aligned}$$

- **Digester**

$$C_e = 2000000 \$ \quad \text{(Market price)}$$

- **Absorber**

$$\text{Height of column} = 5.57 \text{ m}$$

$$\text{Diameter of column} = 1.09 \text{ m}$$

From appendix

$$\text{➤ Vessel cost} = 10100 \text{ \$}$$

$$\text{Packing height} = 4.57 \text{ m}$$

$$\text{Cost} = 960 \text{ \$ / m}^3$$

$$\text{Volume of packing} = \pi * r^2 * h$$

$$\text{Volume} = 3.14 * 0.297 * 4.57 = 4.26 \text{ m}^3$$

$$\text{➤ Cost of packing} = 960 * 4.26 = 4091.75 \text{ \$}$$

$$\text{Total cost of absorber} = 14191.75 \text{ \$}$$

- **Stripper**

$$\text{Height of column} = 2.14 \text{ m}$$

$$\text{Diameter of column} = 1 \text{ m}$$

From appendix

$$\text{➤ Vessel cost} = 7000 \text{ \$}$$

$$\text{Packing height} = 1.9 \text{ m}$$

$$\text{Cost} = 960 \text{ \$ / m}^3$$

$$\text{Volume of packing} = \pi * r^2 * h$$

$$\text{Volume} = 3.14 * 0.25 * 1.9 = 1.49 \text{ m}^3$$

$$\text{➤ Cost of packing} = 960 * 1.49 = 1431.84 \text{ \$}$$

$$\text{Total cost of Stripper} = 8431.84 \text{ \$}$$

- **Heat exchanger**

$$\text{Area of heat exchanger} = 58.5 \text{ m}^2$$

Material = stainless steel

$$\text{Cost} = 70000 * 0.8$$

$$= 56000 \$$$

(Using Appendix)

- **Cooler**

$$\text{Area of heat exchanger} = 38.28 \text{ m}^2$$

Material = stainless steel

$$\text{Cost} = 55000 * 0.8$$

(Using Appendix)

$$= 44000 \$$$

- **Reboiler**

$$\text{Area of heat exchanger} = 11.7 \text{ m}^2$$

Material = stainless steel

$$\text{Cost} = 22000 * 1.3$$

(Using Appendix)

$$= 27300 \$$$

- **Mixer**

$$C_e = 2400 * 7^{0.6}$$

$$= 7713.88 \$$$

- **Flash drum**

$$C_e = 2200 * 25^{0.6}$$

$$= 15178 \$$$

- **Pump**

$$C_e = 300 * 2 \quad (\text{Market Price})$$
$$= 600 \$$$

8.5 Physical Cost of Equipment

Total cost of the equipment = PCE = \$6.5 M

8.6 Plant Physical Cost

Plant physical cost = PPC = PCE * (1 + f₁ + f₂ + ... + f₉)

- Piping = 0.7
- Equipment erection = 0.4
- Instrumentation = 0.2
- Electrical = 0.1
- Utilities = 0.5
- Storage = 0.15

$$PPC = 6.5 * (1 + 0.7 + 0.4 + 0.2 + 0.1 + 0.5 + 0.15)$$

Total PPC = \$13.43 M

8.7 Fixed Capital cost

Fixed capital = PPC * (1 + f₁₀ + ... + f₁₂)

Contingencies = 0.1

Fixed capital cost = 13.43 * (1 + 0.1)

$$= \$14.7 \text{ M}$$

8.8 Working capital

Working Capital = 5% of Fixed capital

$$= 0.05 * (14.7\text{M}) = \$739052$$

Total Investment

Total investment = fixed capital + working capital

$$= 14.7 + 0.739 = \mathbf{\$15.52\text{ M}}$$

8.9 Operating duration

Plant attainment = 95%

Hours operated = $0.95 * 24 * 365$

$$= 8322\text{ hr/year} = 347\text{ days/year} = 11.55\text{ months/year}$$

8.10 Production Cost

- **Variable cost**

Utilities cost

$$\text{Steam} = 12 * 8328 * (300 / 1000) = \$29980.8$$

After multiplying by inflation

$$= 29980.8 * 1.4 = \$41973.12$$

Raw material = \$2067 / year

- **Fixed cost**

Maintenance cost = 5% of FC

$$= \$739052$$

$$\begin{aligned}\text{Operating cost} &= 30\% \text{ of FC} \\ &= 0.3 * 14.7\text{M} \\ &= \$42000\end{aligned}$$

$$\begin{aligned}\text{Plant overhead} &= 50\% \text{ of operating cost} \\ &= 0.5 * 42000 \\ &= \$21000\end{aligned}$$

$$\begin{aligned}\text{Lab cost} &= 30\% \text{ of operating cost} \\ &= 0.3 * 42000 \\ &= \$12600\end{aligned}$$

Annual operating cost = **\$0.96 M**

Mass flowrate of CH₄ = 523.25 kg/hr

Annual production = operating hours * mass flowrate of CH₄

$$= 8322 * 523.25$$

$$= 4354486.5 \text{ kg/yr}$$

Production cost = Annual production cost / Annual production rate

$$= 961731 / 4354486.5$$

$$= \mathbf{0.22 \text{ kg/yr}}$$

8.11 Profit revenue calculations

Selling price = \$1.27/kg

Revenue = selling price * annual production

$$= 1.27 * 4354486.5 = \mathbf{\$5.5 \text{ M / yr}}$$

8.12 Payback period

Break-even point = fixed capital cost / revenue

$$= 14.7 / 5.5$$

Pay Back Period = 2.67 Years

Rate of return = (net cash flow / initial investment) * 100

$$= (5.5 / 14.5) * 100$$

$$= \mathbf{37.41\%}$$

The payback time 2.67 years and the rate of return of 37.41% concludes that over project is feasible and can be applied on a large-scale area.

HAZOP ANALYSIS

9.1 Hazard and operability studies

The HAZOP study is a formal procedure to identify hazards in a chemical process facility. The procedure is effective in identifying hazards and is well accepted by the chemical industry.

9.2 Steps involved

The HAZOP procedure uses the following steps to complete an analysis

- Detailed flow sheet
Break the flow sheet into several process units. Thus, the reactor area might be one unit and the mixer another. Select a particular unit for study.
- Choose a study node
Select a study node of that process unit.
- Design intent of node
Describe the design intent of that node, for example agitator is used to mix wastewater and manure in correct proportion.
- Process parameter
Pick a process parameter which is under consideration, for example flow, level, volume, reaction, agitation, pH, viscosity, power, inert etc.
- Apply guide word
Use a guide word for process parameter to suggest possible deviation, for example NO, MORE, AS WELL AS, REVERSE, WHERE ELSE etc.
- Determine cause
If deviation is applicable, determine the possible causes and note any protective system.
- Consequence
Determine that if deviations occur then what are its consequences.

- Recommended actions
 - Note down the recommended actions that can be taken for deviations
- Record
 - Make a record of all the information for further use.

9.3 Digester

Study node: digester

Table 38 HAZOP of Digester

Parameter	Guide word	Deviation	Possible causes	Consequences	Action
Flow	No	No flow coming out	Blockage in the pipe.	Overflow of effluent pit in the digesters	Implement alarm at high level Consider flushing points in pipework
	Reverse		Common Overflows	Cross venting (Biogas and air)	Confirm pipework design
Temperature	Less	Temperature less than 35°C	Feed has lower temperature.	Microbial/Biogas Production activity would be affected.	Installation of thermocouples. Interlocking
Composition	As well as / other	Impurities	Feed with different composition	Microbial activity is very sensitive to conditions. Biogas production will be decreased.	Installation of feed analyzer. Installation of pH meter in digester.

9.4 Mixer

Study node: impellers

Parameter: agitation

Table 39 HAZOP of Mixer

Guide word	Deviation	Possible Causes	Consequences	Action
No	Agitation stops	Power Failure Agitation motor Malfunction	Improper mixing Non-uniform Temperature distribution. Microorganism may die.	Interlocking Keep agitation motor in critical instrument list.
More	Agitation is increased	Stirrer motor controller fails,	Vortex formation led to improper mixing.	Proper checking of agitator motor.

9.4 Absorber

Study node: biogas inlet stream

Parameter: flow

Table 40 HZAOP of Absorber

Guide word	Deviation	Possible causes	Consequences	Action
Less / No	Biogas is not entering Absorber	Digester is not functioning, Leakage Valve is closed or not working.	Absorption column will not work effectively. MEA solution will go untreated. Channeling	Installation of flow meter in Biogas pipeline. Interlocking
As well As	Composition of Biogas is changed	Condition inside digester lead to change composition. Air entering in line.	Absorption process will be affected.	Installation of Gas Analyzer meter.

9.5 Heat exchanger

Study node: hot amine out

Parameter: flow

Table 41 HAZOP of Heat Exchanger

Guide Word	Deviation	Possible Causes	Consequences	Action
As well as	Impurities	Presence of contaminants in feed	Affect the performance. Scaling and corrosion	Take the samples of Rich Amine regularly. Tube maintenance.
Less / No	No or very Little Flow	Plugging of tubes.	Stripper working will be affected.	Low Flow Alarm Install filter with maintenance. Scheduled cleaning of tubes.
More of	More Flow	Valve fails due to which feed flow rate increases	Quantity of feed increases thereby increasing load on tubes. Improper Heat Transfer	High flow alarm. Install a bypass Valve.
None	No Flow	Failure of Pump	No heat transfers.	Maintenance of valve. Proper inspection.

CONCLUSION

In conclusion, various types of equipment and devices have been designed to facilitate the economic & energy needs of human beings due to technological developments in present. Continuous Anaerobic system that uses Industrial and Municipal Waste Water as its raw material has been successfully designed to facilitate the human life. All of the objectives, that we discussed in our project have been successfully completed on the proper timeline. During the Energy Balance, it's been concluded that a massive amount of Heat Energy would be produced that can help meet the energy crisis of the people as well as the country too; whereas the energy required to run the plant is comparatively very less.

Cost analysis concludes that the project is quite feasible with a payback period of 2.7 years to install and keep it into operation. Cost of electricity produced will be lower and the society will feel less burden for electricity. From the Environmental point of view, it can be concluded that this project has met its SDG of clean environment and Sanitation; as it involves removal of contaminants from waste water along with making it non-poisonous for the marine as well as human life. It also includes reduction in GHG and land, water pollution too.

RECOMMENDATIONS

This system can also be implemented on a large-scale Field area; or multiple small scales or different locations. Having more systems like this, amount of waste water generating every day would be consumed in a way that it will eventually help the society and the country economically and environmentally.

For the future Recommendations; improvements can be made in the plant such as installation of good filters and grit removers; so that the unwanted contaminants would be removed beforehand. This will help reduce the volume of waste water even more and eventually the actually wanted solids will be introduced in the digester. Preventive measures can be introduced that will help run the system efficiently and reducing the chances of risk. Regular maintenance of the digester and the plant as well would increase the plant life. Install a better post treatment system that will further help to purify or increase the concentration of Methane; thus, reducing the unwanted gases in it.

APPENDIX

➤ **Figure 1**

Table 11.2. Design data for various packings

	Size		Bulk density (kg/m ³)	Surface area <i>a</i> (m ² /m ³)	Packing factor <i>F_p</i> m ⁻¹
	in.	mm			
Raschig rings	0.50	13	881	368	2100
ceramic	1.0	25	673	190	525
	1.5	38	689	128	310
	2.0	51	651	95	210
	3.0	76	561	69	120
Metal	0.5	13	1201	417	980
(density for carbon steel)	1.0	25	625	207	375
	1.5	38	785	141	270
	2.0	51	593	102	190
	3.0	76	400	72	105
Pall rings	0.625	16	593	341	230
metal	1.0	25	481	210	160
(density for carbon steel)	1.25	32	385	128	92
	2.0	51	353	102	66
	3.5	76	273	66	52
Plastics	0.625	16	112	341	320
(density for polypropylene)	1.0	25	88	207	170
	1.5	38	76	128	130
	2.0	51	68	102	82
	3.5	89	64	85	52
Intalox saddles	0.5	13	737	480	660
ceramic	1.0	25	673	253	300
	1.5	38	625	194	170
	2.0	51	609	108	130
	3.0	76	577		72

➤ Figure 2

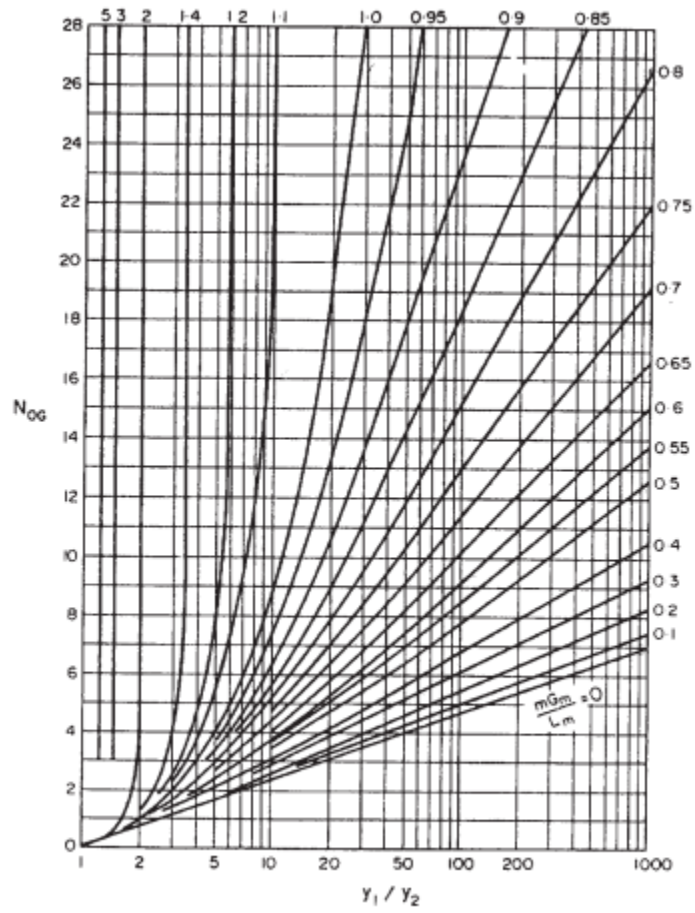
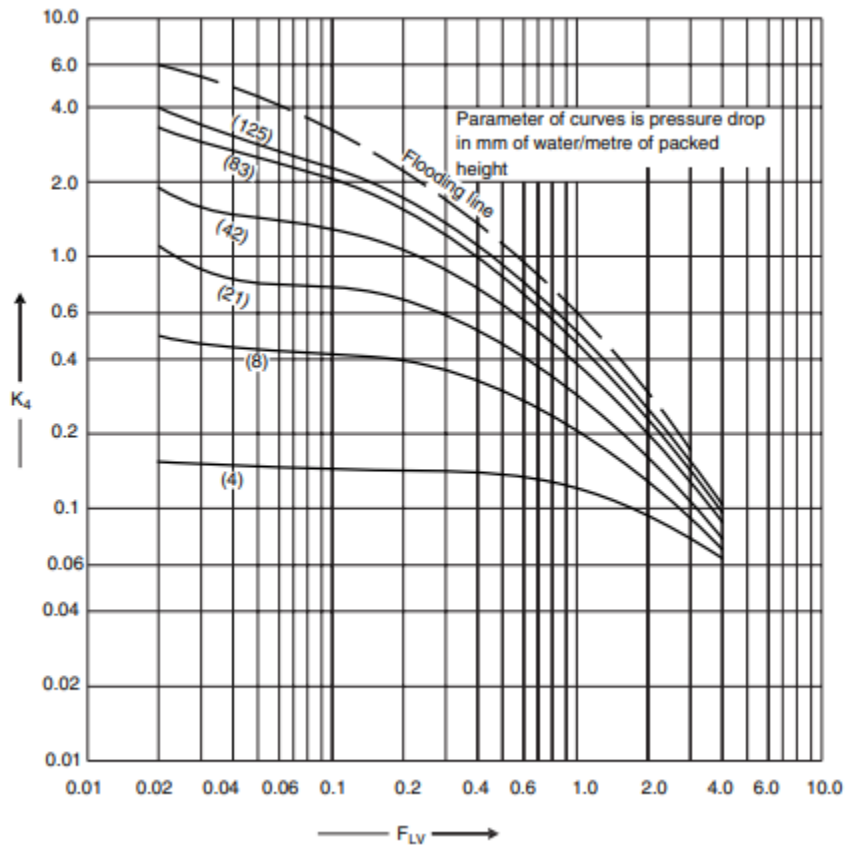


Figure 11.40. Number of transfer units N_{OG} as a function of y_1/y_2 with mG_m/L_m as parameter

➤ Figure 3



➤ Figure 5

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CHEMICAL ENGINEERING

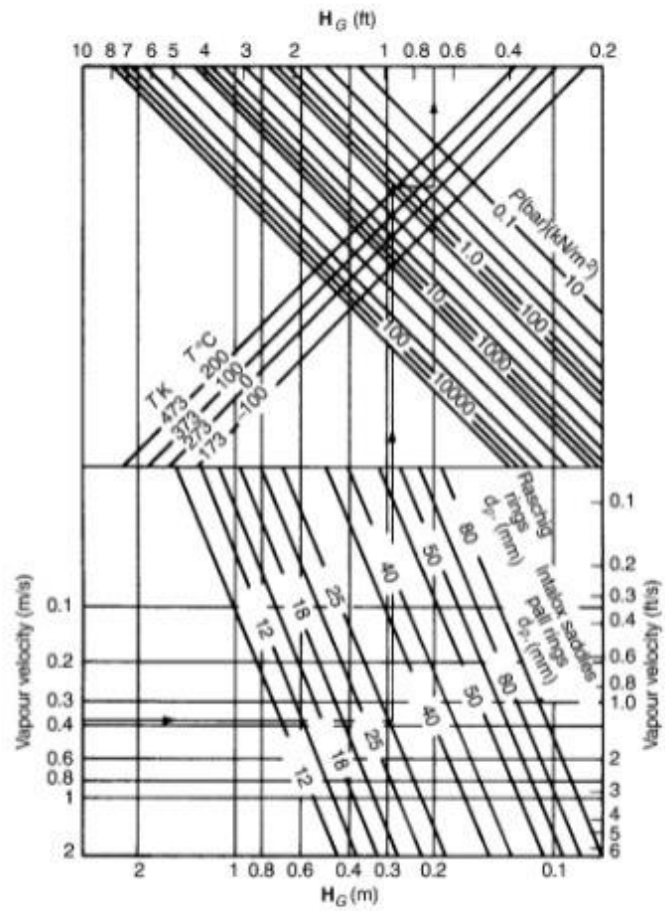
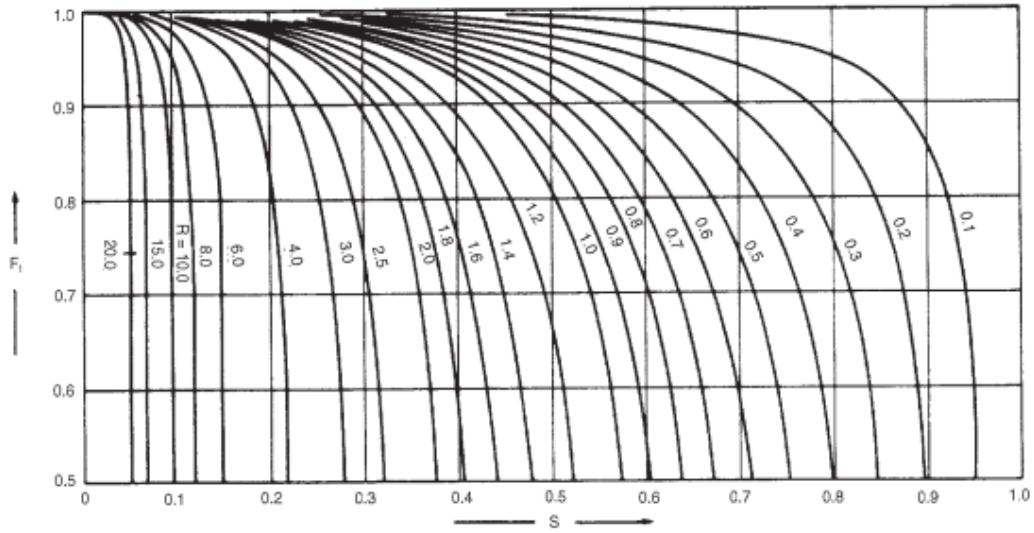
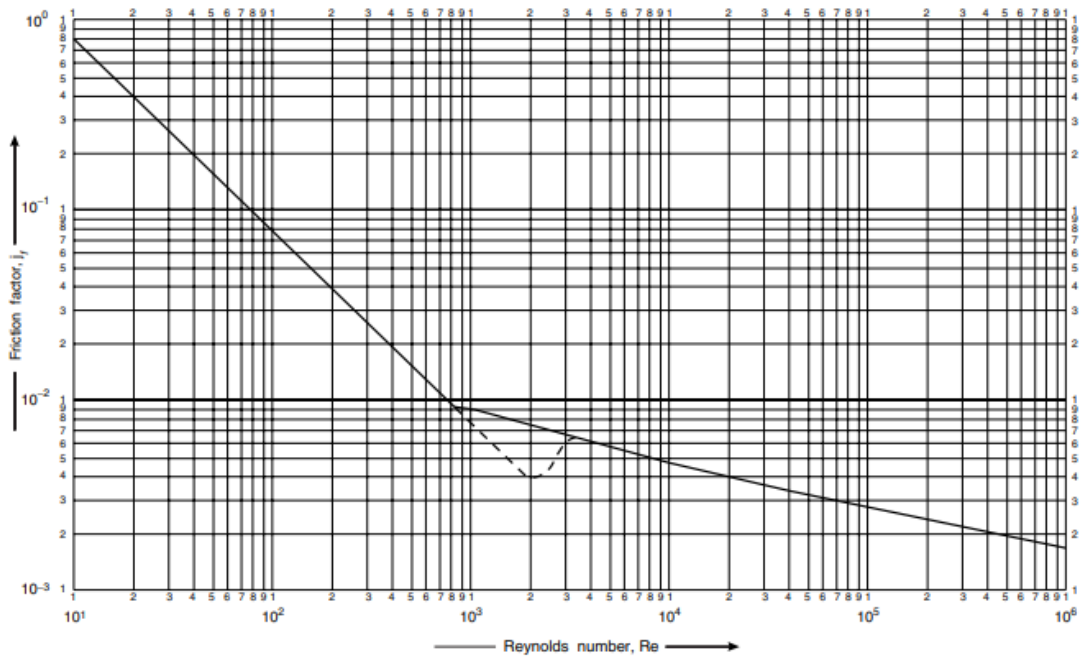


Figure 12.21. Nomograph for the estimation of the height of a gas-phase transfer unit⁽⁵⁴⁾

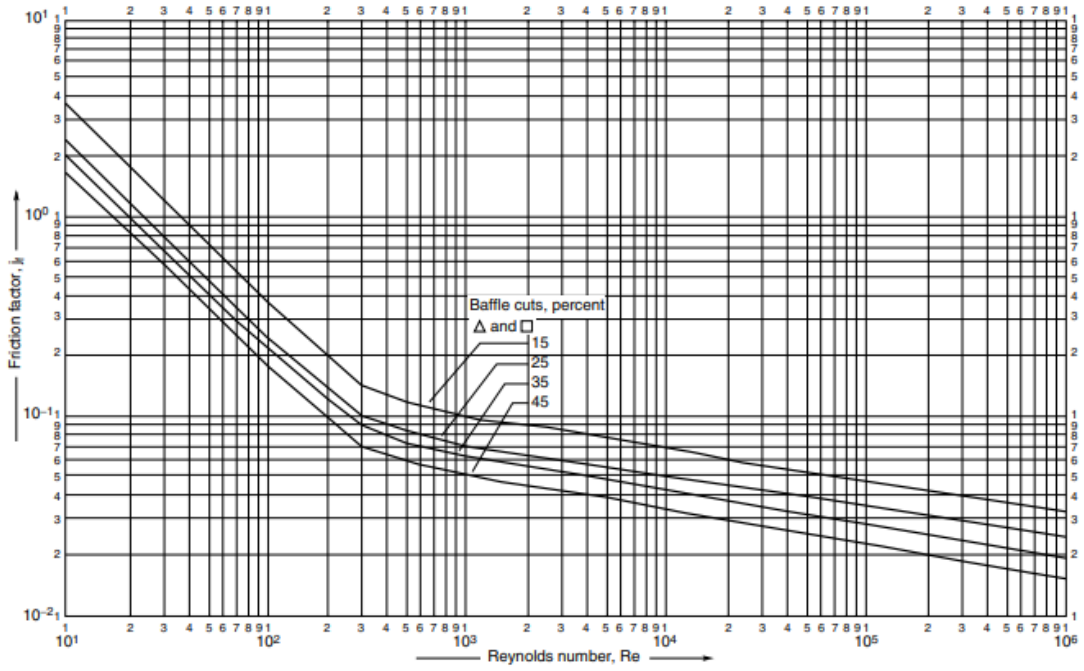
➤ Figure 6



➤ Figure 7



➤ Figure 8



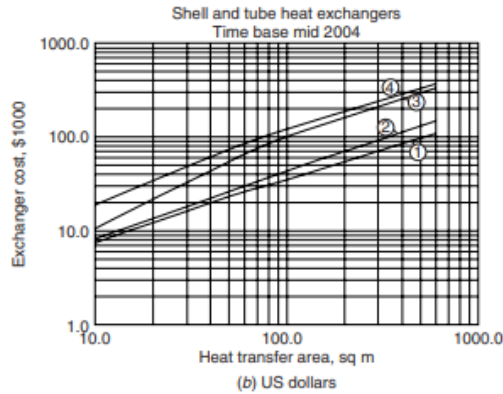
➤ Figure 9

TABLE 9. TUBE-SHEET LAYOUTS (TUBE COUNTS)
Square Pitch

¾ in. OD tubes on 1-in. square pitch						1 in. OD tubes on 1¼-in. square pitch					
Shell ID, in.	1-P	2-P	4-P	6-P	8-P	Shell ID, in.	1-P	2-P	4-P	6-P	8-P
8	32	26	20	20		8	21	16	14		
10	52	52	40	36		10	32	32	26	24	
12	81	76	68	68	60	12	48	45	40	38	36
13¼	97	90	82	76	70	13¼	61	56	52	48	44
15¼	137	124	116	108	108	15¼	81	76	68	68	64
17¼	177	166	158	150	142	17¼	112	112	96	90	82
19¼	224	220	204	192	188	19¼	138	132	128	122	116
21¼	277	270	246	240	234	21¼	177	166	158	152	148
23¼	341	324	308	302	292	23¼	213	208	192	184	184
25	413	394	370	356	346	25	260	252	238	226	222
27	481	460	432	420	408	27	300	288	278	268	260
29	553	526	480	468	456	29	341	326	300	294	286
31	657	640	600	580	560	31	406	398	380	368	358
33	749	718	668	676	648	33	465	460	432	420	414
35	845	824	780	766	748	35	522	518	488	484	472
37	934	914	866	866	838	37	586	574	562	544	532
39	1049	1024	962	968	948	39	665	644	624	612	600

1¼ in. OD tubes on 1½-in. square pitch						1½ in. OD tubes on 1⅝-in. square pitch					
10	16	12	10			12	16	16	12	12	
12	30	24	22	16	16	12	22	22	16	16	
13¼	32	30	30	22	22	13¼	22	22	16	16	
15¼	44	40	37	35	31	15¼	29	29	25	24	22
17¼	56	53	51	48	44	17¼	39	39	34	32	29
19¼	78	73	71	64	56	19¼	50	48	45	43	39
21¼	96	90	86	82	78	21¼	62	60	57	54	50
23¼	127	112	106	102	96	23¼	78	74	70	66	62
25	140	135	127	123	115	25	94	90	86	84	78
27	166	160	151	146	140	27	112	108	102	98	94
29	193	188	178	174	166	29	131	127	120	116	112
31	226	220	209	202	193	31	151	146	141	138	131
33	258	252	244	238	226	33	176	170	164	160	151
35	293	287	275	268	258	35	202	196	188	182	176
37	334	322	311	304	293	37	224	220	217	210	202
39	370	362	348	342	336	39	252	246	237	230	224

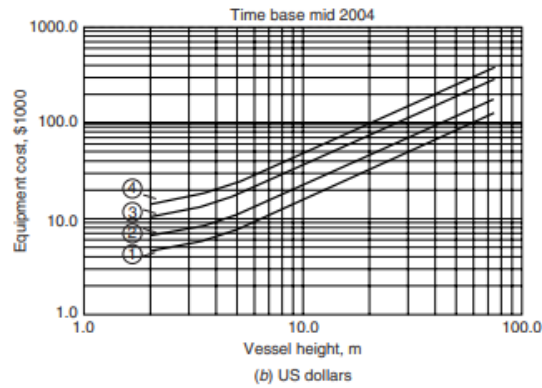
➤ **Figure 10**



Materials		Pressure factors	Type factors
Shell	Tubes		
① Carbon steel	Carbon steel	1-10 bar × 1.0	Floating head × 1.0
② C.S.	Brass	10-20 × 1.1	Fixed tube sheet × 0.8
③ C.S.	Stainless steel	20-30 × 1.25	U tube × 0.85
④ S.S.	S.S.	30-50 × 1.3	Kettle × 1.3
		50-70 × 1.5	

Figure 6.3a, b. Shell and tube heat exchangers. Time base mid-2004
Purchased cost = (bare cost from figure) × Type factor × Pressure factor

➤ **Figure 11**



Diameter, m	Material factors	Pressure factors
① — 0.5 ③ — 2.0	C.S. × 1.0	1-5 bar × 1.0
② — 1.0 ④ — 3.0	S.S. × 2.0	5-10 × 1.1
	Monel × 3.4	10-20 × 1.2
	S.S. clad × 1.5	20-30 × 1.4
	Monel clad × 2.1	30-40 × 1.6
		40-50 × 1.8
		50-60 × 2.2

Temperature up to 300°C

Figure 6.5a, b. Vertical pressure vessels. Time base mid-2004.
Purchased cost = (bare cost from figure) × Material factor × Pressure factor

➤ Figure 12

Table 6.2. Purchase cost of miscellaneous equipment, cost factors for use in equation 6.7. Cost basis mid 2004

Equipment	Size unit, S	Size range	Constant		Index n	Comment
			C,£	C,\$		
Agitators						
Propeller	driver	5-75	1200	1900	0.5	
Turbine	power, kW		1800	3000	0.5	
Boilers						
Packaged	kg/h steam	(5-50) × 10 ³	70	120	0.8	oil or gas fired
up to 10 bar			60	100	0.8	
10 to 60 bar						
Centrifuges						
Horizontal basket	dia., m	0.5-1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	× 1.7 for ss
Compressors						
Centrifugal	driver	20-500	1160	1920	0.8	electric,
Reciprocating	power, kW		1600	2700	0.8	max. press. 50 bar
Conveyors						
Belt	length, m	2-40				
0.5 m wide			1200	1900	0.75	
1.0 m wide			1800	2900	0.75	
Crashers						
Cone	t/h	20-200	2300	3800	0.85	
Pulverisers	kg/h		2000	3400	0.35	
Dryers						
Rotary	area, m ²	5-30	21,000	35,000	0.45	direct
Pan		2-10	4700	7700	0.35	gas fired
Evaporators						
Vertical tube	area, m ²	10-100	12,000	20,000	0.53	carbon steel
Falling film			6500	10,000	0.52	
Filters						
Plate and frame	area, m ²	5-50	5400	8800	0.6	cast iron
Vacuum drum		1-10	21,000	34,000	0.6	carbon steel
Furnaces						
Process						
Cylindrical	heat abs, kW	10 ³ -10 ⁴	330	540	0.77	carbon steel
Box		10 ³ -10 ⁵	340	560	0.77	× 2.0 ss
Reactors						
Jacketed, agitated	capacity, m ³	3-30	9300	15,000	0.40	carbon steel
			18,500	31,000	0.45	glass lined
Tanks						
Process	capacity, m ³					
vertical		1-50	1450	2400	0.6	atmos. press.
horizontal		10-100	1750	2900	0.6	carbon steel
Storage						
floating roof		50-8000	2500	4350	0.55	× 2 for
cone roof		50-8000	1400	2300	0.55	stainless

Table 6.3. Cost of column packing. Cost basis mid 2004

Size, mm	Cost		
	£/m ³	\$/m ³	
25	38	50	
Saddles, stoneware	840 (1400)	620 (1020)	580 (960)
Pall rings, polypropylene	650 (1080)	400 (650)	250 (400)
Pall rings, stainless steel	1500 (2500)	1500 (2500)	830 (1360)

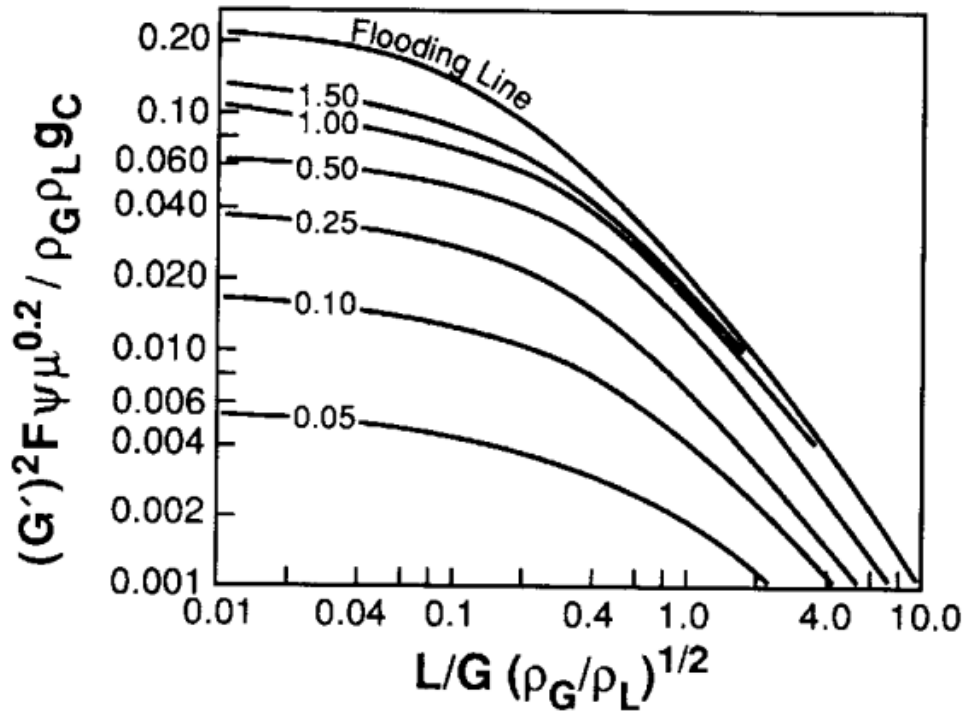
➤ Figure 13

Table 6.1. Typical factors for estimation of project fixed capital cost			
Item	Process type		
	Fluids	Fluids-solids	Solids
1. Major equipment, total purchase cost	PCE	PCE	PCE
f_1 Equipment erection	0.4	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
f_6 Utilities	0.50	0.45	0.25
f_7 Storages	0.15	0.20	0.25
f_8 Site development	0.05	0.05	0.05
f_9 Ancillary buildings	0.15	0.20	0.30
2. Total physical plant cost (PPC)	PPC = PCE (1 + $f_1 + \dots + f_9$) = PCE ×		
	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital = PPC (1 + $f_{10} + f_{11} + f_{12}$) = PPC ×	1.45	1.40	1.35

*Omitted for minor extensions or additions to existing sites.

Table 6.6. Summary of production costs		
<i>Variable costs</i>		<i>Typical values</i>
1. Raw materials		from flow-sheets
2. Miscellaneous materials		10 per cent of item (5)
3. Utilities		from flow-sheet
4. Shipping and packaging		usually negligible
	Sub-total A
<i>Fixed costs</i>		
5. Maintenance		5-10 per cent of fixed capital from manning estimates
6. Operating labour		20-25 per cent of 6
7. Laboratory costs		20 per cent of item (6)
8. Supervision		50 per cent of item (6)
9. Plant overheads		10 per cent of the fixed capital
10. Capital charges		1 per cent of the fixed capital
11. Insurance		2 per cent of the fixed capital
12. Local taxes		1 per cent of the fixed capital
13. Royalties	
	Sub-total B
	Direct production costs A + B
13. Sales expense		20-30 per cent of the direct production cost
14. General overheads	
15. Research and development	
	Sub-total C
	Annual production cost = A + B + C =
	Production cost £/kg =	Annual production cost / Annual production rate

➤ Figure 14



Correlation for estimating tower cross sectional area.

➤ Figure 15

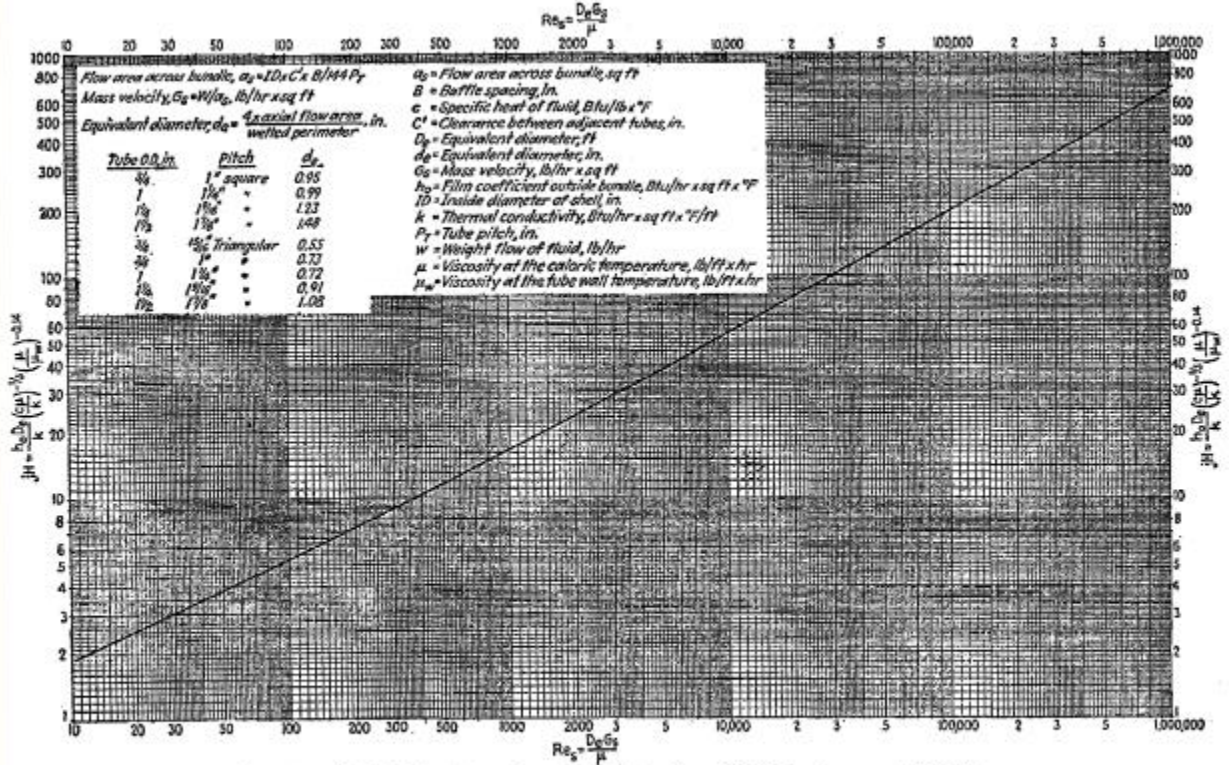


FIG. 28. Shell-side heat-transfer curve for bundles with 25% cut segmental baffles.

➤ Figure 16

TABLE 10. HEAT EXCHANGER AND CONDENSER TUBE DATA

Tube OD, in.	RWG	Wall thickness, in.	TD, in.	Flow area per tube, in. ²	Surface per lin ft, ft ²		Weight per lin ft, lb steel
					Outside	Inside	
1/2	12	0.109	0.282	0.0625	0.1309	0.0748	0.493
	14	0.083	0.334	0.0876		0.0874	0.403
	16	0.065	0.370	0.1076		0.0969	0.329
	18	0.049	0.409	0.127		0.1052	0.258
	20	0.035	0.430	0.145		0.1125	0.190
3/4	10	0.134	0.482	0.182	0.1963	0.1263	0.965
	11	0.120	0.510	0.204		0.1335	0.884
	12	0.109	0.532	0.223		0.1393	0.817
	13	0.095	0.560	0.247		0.1466	0.727
	14	0.083	0.584	0.268		0.1529	0.647
	15	0.072	0.606	0.289		0.1587	0.571
	16	0.065	0.620	0.302		0.1623	0.520
	17	0.058	0.634	0.314		0.1660	0.469
	18	0.049	0.652	0.334		0.1707	0.401
1	8	0.165	0.670	0.355	0.2618	0.1754	1.61
	9	0.148	0.704	0.389		0.1843	1.47
	10	0.134	0.732	0.421		0.1916	1.36
	11	0.120	0.760	0.455		0.1990	1.23
	12	0.109	0.782	0.479		0.2048	1.14
	13	0.095	0.810	0.515		0.2121	1.00
	14	0.083	0.834	0.546		0.2183	0.890
	15	0.072	0.856	0.576		0.2241	0.781
	16	0.065	0.870	0.594		0.2277	0.710
1 1/4	8	0.165	0.920	0.665	0.3271	0.2409	2.09
	9	0.148	0.954	0.714		0.2498	1.91
	10	0.134	0.982	0.757		0.2572	1.75
	11	0.120	1.01	0.800		0.2644	1.58
	12	0.109	1.03	0.836		0.2701	1.45
	13	0.095	1.06	0.884		0.2775	1.28
	14	0.083	1.08	0.923		0.2839	1.13
	15	0.072	1.11	0.960		0.2896	0.991
	16	0.065	1.12	0.985		0.2932	0.900
1 1/2	8	0.165	1.17	1.075	0.3925	0.3063	2.57
	9	0.148	1.20	1.14		0.3152	2.34
	10	0.134	1.23	1.19		0.3225	2.14
	11	0.120	1.26	1.25		0.3299	1.98
	12	0.109	1.28	1.29		0.3356	1.77
	13	0.095	1.31	1.35		0.3430	1.56
	14	0.083	1.33	1.40		0.3492	1.37
	15	0.072	1.36	1.44		0.3555	1.20
	16	0.065	1.37	1.47		0.3587	1.09
17	0.058	1.38	1.50	0.3623	0.978		
18	0.049	1.40	1.54	0.3670	0.831		

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