Design of Auto Mix Single Stage Anaerobic Digester and Aspen plus Simulation for Biogas Production

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By

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This is to certify that M.Tech Dual degree thesis entitled, "**Design of Auto Mix Single Stage Anaerobic Digester and Aspen plus Simulation for Biogas Production**" submitted to the National Institute of Technology Rourkela by **Mr. Srinivas Tenneti** in partial fulfilments for the requirements of the award of Master of Technology degree in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. He has fulfilled all the prescribed requirements and the thesis, which is based on candidate's own work, has not been submitted elsewhere.

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Srinivas Tenneti

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Dedicated to

“The people who taught me to talk and

The talks that taught me to listen”

-Srinivas Tenneti

Contents

ABSTRACT:

Bio fuels have been considered to be the viable alternatives and the supportive sources for the depleting fossil fuels under the objective of satisfying the energy demand. Considering the two fold importance of bioenergy production and the subsequent reduction of waste accumulation, the work explored the possibility of biogas production in various operational scales. The present work can be categorized into two parts.

In the first part, the work has surveyed various digester designs under operation and focused on the mixing and intermittent aeration that are not under light in the regular practice. The digester gas collector configuration that could promote the mixing and intermittent aeration was designed. The setup was run on 20 L scale with an objective of observing the gas production phenomenon. The recommended operational solutions were modified and implemented in the form of a 50 L digester setup to observe the performance improvements in attaining self-buffering capacity and sensitivity to the acidic feed stocks. Further suggested modifications lead to the final design that could promote intermittent aeration and mix the digester constituents without the use of impeller and with minimal or no power consumption depending on the amount of gas produced. An advanced design called compartmental digester design was next presented for the medium to large scale applications which was run on 200 L scale in a semi continuous mode using cow dung as substrate and was tested for the feasibility.

The second part of our work focused on simulation of a two stage anaerobic digester configuration for studying the kinetics of hydrolysis, acidogenesis and acetogenesis and methanogenesis in three different reactors. In this study, kitchen waste stream were analysed for biogas production which was compared with the results of NISARGRUNA biogas plant (BARC) for the validation of the model and the model with same kinetics was then used to analyse the gas production from poultry manure.

Keywords: Biogas, microbial culture, mesophilic phase, inoculum and methanogens.

List of Tables

List of Figures:

Chapter 1

INTRODUCTION

Energy crisis and waste disposal are the two main interdependent problems of main concern in a developed country like India in the present scenario. India is mainly dependent in thermal power means of energy production and is the third largest consumer of coal in the world [23]. Thermal means of energy production not only results in enormous pollution but also responsible for the depletion of fossil fuels. In the second perspective, disposal grounds and dumping yards are the nuisance to the present society leading to the leachate emissions which would not only cause cancer diseases but also pollute ground water reserves. Unsegregated form of waste disposal is the main cause for this problem. Present day per capita waste disposal is 0.34 KGs [25] out of which 40-50 percent is the organic and biodegradable which is expected to reach 0.7 KGs by the year 2030 [25].

Rate of waste disposal and deposition shows consistent rise whereas rate of decomposition is heavily disturbed by the presence of non-degradable substances like plastics and metal deposits causing the accumulation and insufficiency of dump yards. In the rural domain of India, even though there is availability of concentrated form of bio wastes in the form of agricultural residues and animal manures, efforts by innovators and NGOs in the form of biogas plant installations failed to be implemented for longer times in most places. The reason could be lack of awareness regarding the importance of bio energy production and the energy production not being the primary means of living.

Understanding the scenario, theoretical as well as field review has been conducted on the conventional bio digester designs under the implementation. As a part of theoretical survey, digester designs like fixed dome, floating drum, horizontal designs etc. have been studied for the applicable scales of operations, operational constraints and advantages and disadvantages of operation which are explained in chapter 3. The observations showed lack of proper mixing and intermittent aeration in the conventional digester designs.

1.1 Problem statement 1: Lack of mixing and intermittent aeration

Biogas produced in the rural and domestic plants is mostly used for the combustion purposes and is treated as the by product which is the fact driving the plants to lack proper sophistication.

1.1.1 Necessity of mixing and intermittent aeration:

Mixing of the substrate during anaerobic digestion process increases the availability of the substrate to the microbes and the enzymes. This process as a whole reduces the HRT (hydraulic retention time) and increases the capacity of operation. ARTI design invented by Dr Anand Karve (2003) uses HRT of 42.5 days to compensate for the lack of mixing [29] and promote complete degradation. On contrary, biogas plant in the effluent treatment plant of United Breweries Spirits Limited at Hospeta, Karnataka operates at the HRT of 19 days using recycling pumps acting as longitudinal mixers to provide axial mixing. This shows that the scale of operation can be increased by nearly 2.2 times by providing proper mixing mechanism in the digester. Apart from that, mixing also maintains uniform operational parameters in the digesters which would result in the consistent and uniform microbial density rather that colonial formation and improper distribution of microbes. Mixing reduces the scum formation, entrapment of gas bubbles in the bottom layers of digesters and there by prevents the loss of gas in the form of bubbles from the effluent stream.

Intermittent and periodical aeration is definitely an asset to the degradation of the volatile solids in the digester. Periodical aeration of the substrate enhances acidogen activity which inturn maintains required enzyme concentration and thus improve degradation. High rates of hydrolysis and acidogenesis reduces the solid concentration in the slurry and therefore efforts in the form of mixing to reduce the sedimentation is reduced. This results in reduction of energy consumption. Also intermittent aeration results increases the oxygen content in the slurry and reduces the concentration of H_2S in the biogas.

1.1.2 Reasons for not being practiced:

Mixing and intermittent aeration are not practiced mainly because of the additional sophistication and energy requirement imposed on the plant. Impeller and motor installation and maintenance also increase the payback period of the biogas plant and as the biogas production is a by production operation in many situations, these phenomena are not in light.

1.2 Problem statement 2:

Two stage digestion process is much more efficient both in terms of gas production as well as the concentration of methane in the gas outlet stream compared to the single stage anerobic digesters. NISARGRUN digester configuration invented by Dr Sharad Kalae from Bhaba Atomic Research Centre Mumbai, India in the year 2003 is feasible in operation in 0.5 tonnes of waste per day to 10 and above tonnes per day. However it is only popular in Maharashtra and some places in India. The process simulation model involving the detailed kinetics of given by Angediki et al. [26] and Karthik Rajendran et al. [27] was validated only in laboratory scales. The model if studied in the operational scales of NISARGRUN would be very much applicative and makes the complexes of anaerobic digestion process more a solved problem.

1.3 Research Objective:

1. Considering the mentioned aspects and the importance of mixing and aeration of the slurry, a digester gas collector configuration that could automatize mixing with minimal added sophistication, less power consumption and easier maintenance has to be designed for both domestic scale as well as large scale applications.
2. Process simulation model has to be modified in the scale of operation of NISARGRUN and studied for the gas production using varieties of feed stocks and has to be validated. The model should then be used to give the appropriate gas production details based on the type and nature of substrate supplied to the simulator.

Chapter 2

THEORY

2.1 Biodegradation:

Biodegradation is the process of digestion of organic substances in under the action of microbes and the influence of enzymes that catalyse the degradation process at the suitable operational conditions. Two types of biodegradation is under practice which include aerobic digestion in which microbes degrade the substrate in the presence of oxygen and anaerobic digestion in which organic substrates are degraded in the absence of oxygen.

2.2 Anaerobic digestion:

2.2.1 History:

Anaerobic digestion was first discovered when the lights were observed from the below surface of swamps by Plinius and Van Helmont. During the year of 1776, the conclusion was made regarding the phenomenon of gas production stating that the amount of gas release is proportional to extent of the degradation of vegetative matter. During the span of 1804 to 1810, Dalton, Henry and Darvy calculated the chemical composition of methane and concluded the similarity between coal and Voltas marsh gas. 19^{th} century was the time of conclusion of microbial activity being responsible for anaerobic digestion. This is the start of commercialization of the process and subsequently cow dung was fermented first in the France to produce the biogas. Street used to be lighted in the England by using the gas produced from the anaerobic digestion of animal and human manures. Later came the era of digester designs which could bring the production to individual applications [28].

2.2.2 Stages of Anaerobic digestion:

Anaerobic digestion involves mainly 4 stages of degradation

i. Hydrolysis:

In this process complex organic biodegradable compounds such as carbohydrates, proteins and lipids degrade into the respective monomers by FOAB (facultative and obligatory anaerobic bacteria). Carbohydrates such as cellulose, hemi cellulose and starch degrade into their monomers include glucose, dextrose and xylose whereas proteins degrade into 23 types of amino acids and lipids degrade into glycerol and the other corresponding monomers. This process requires high water content and the monomers resulting from the reaction are water soluble. For the complete degradation, carbohydrates take hours whereas proteins and fats take time in the order of days [12].

ii. Acidogenesis:

The process of acidogenesis is performed by the action of aerobic bacteria and the monomers are further degraded into short chain molecules in this process. The monomers of carbohydrates and fats generally produce volatile fatty acids such as acetic acid, butyric acid, propionic acid, valeric acid etc. and the traces of carbon dioxide. Amino acid produce ammonia in addition to carbon dioxide and volatile fatty acids. Glycerol produces VFA, ethanol and carbon dioxide. The constituents from acidogenic phase are highly acidic in nature and if produced in uncontrolled manner, the anaerobic digester would turn into sour and the methane production is significantly affected.

iii. Acetogenesis:

The main purpose of acetogenesis is the further degradation of higher order VFA such as butyric acid, propionic acid and valeric acid etc. into hydrogen acetic acid and the microbial biomass. Ethyl cyano acetate is the compound used to represent the biomass in the anaerobic digestion models. The process utilizes the ammonia produced by amino acid degradation to buid up the cell biomass. Thus protein content plays a crutial role in the cell growth kinetics of FOAB in the bioreactor.

iv. Methanogenesis:

Methanogens need H_2 produced in the acetogenesis phase for the active participation of acetic acid degradation into methane and improving their population. Methane production mainly occurs by the degradation of three types of substrate with the following functional groups such as acetate type (CH_3COO^-) performed by all kinds of methanogenic species, CO_2 type performed by only certain type of methanogens and methyl type functionally grouped monomers are degraded by only rare kind of methanogens. Thus the key assumption in modelling is to assume the methane production takes place mostly from acetic acid and to a small extent by CO_2.

2.3 Parameters affecting anaerobic digestion:

2.3.1 Temperature:

Based on the operational temperatures, the anaerobic digestion procedures can be classified into

a. Psychrophilic digestion:

The operational temperature range is 10 to 25 ^oC and is not possible in India. This process of digestion is economical friendly and natural in the countries hiving cold climatic conditions. The rates of anaerobic digestion are very low and the production is not rapid in this configuration.

b. Mesophilic digestion:

This process is operated at the temperatures in the range of 30 to 42 ^oC and is spontaneous and adaptable procedure in India since it involves no heat exchangers and even though the temperature of the surroundings fall below this range, the exothermic nature of anaerobic digestion releases heat and maintains the temperature in the range of operation.

c. Thermophilic digestion:

This process is operated in the range of 48 to 65 ^{o}C and the rates of digestion are very high the digestion itself is rapid and 1.5 fold higher compared to the mesophilic digestion [12]. This process operates at less residence time and thus at more capacity for a particular reactor volume. Fat type substrates are favourably degraded in thermophilic process and is economical only in the larger operational scales. Yield of biogas is higher in this process.

2.3.2 pH:

pH plays a significant role in the process of methane production. pH in the range of 6.7 to 7.5 is operable for biogas production [12]. Lower pH results in the hampering of methanogenic activity and results in volatile solid accumulation inside the digester. The digester is said to be attained self-buffering capacity if it could be insensitive to the lower input pH. In the anaerobic digester, dissolved ammonia contribute to the basic nature of the digester and dissolved carbon dioxide in the form of carbonic acid contribute to the acidic effect. The balanced production of ammonia and carbonic acid maintain the digester at neutral and operable pH range for optimum methane production.

2.3.3 Nutrient C/N/P ratio:

The ratio of carbon and nitrogen in aqueous state in the substrate plays significant role in the race of gas production and microbial metabolisms. Higher C/N ratio results in the lower availability of nitrogen to the microbial multiplication which reduces microbial growth and effects the production and degradation. Lower C/N ratio results in the ammonia inhibition of methane production. The nutrients ratio C : N :P : S of 500-1000 : 15-20 : 5 : 3 or the organic matter ratio of COD : N : P : S =800 :5 :1 : 0.5 is necessary for optimal methane production.

2.3.4 Pressure:

Pressure inside the digester is again a crucial parameter in the anaerobic digestion process. Higher partial pressure of H_2 would result in the enhanced methanogen activity and reduces the ammonia inhibition. This is because, higher is the pressure more soluble is the ammonia in the aqueous phase. But this will also increase the H_2S formation which would result in the H_2S inhibition of methanogeinc activity. Presence of traces of oxygen in the gas space would oxidize the H_2S into SO_2 and would reduce the concentrations of H_2S in the gas space and promote methanogen activity.

2.3.5 Hydraulic retention time (HRT):

Hydraulic retention time is defined as the ratio of the active digester volume to that of the volumetric flow rate into the digester. HRT usually compensate for the mixing in the digester. Higher HRT would result in the complete digestion but may reduce the capacity and scale of operation where as too lower HRT would increase the disturbance and change of operational parameters such as pH, temperature etc. and affects the gas production. The HRT also does depend on the type and composition of the substrate used for the process but mostly, with the proper mixing of the digester constituents, for a single stage digestion process, HRT around 20 is optimum [1] and without mixing, HRT of the range 30 to 40 is necessary for proper digestion. In a two stage anaerobic digestion process, HRT can be taken till the order of 12 to 15 [31] [32].

2.3.6 Organic loading rate (OLR):

The organic loading rate is defined as the amount in mass (kilo grams) of volatile solids that are introduced into the digester per unit time per unit working volume of the digester. Organic loading rates in the range 1 to 3 kg VS/cubic m/day is good range of operation in the input feed to the digester. OLR crossing 4 kg VS/cubic m/day would result in VFA accumulation and souring of the digester. The gas production is highly hampered in this state and alkaline treatment with $CaCO_3$ would recover the digester from the situation.

2.3.7 Alkalinity:

Alkalinity is defined as the buffering capacity of the water phase to neutralize the acids and is usually the measure of carbonates, bicarbonates, hydroxides and occasionally, borates, silicates, and phosphates. It is expressed in milligrams of equivalent calcium carbonate per litre. The optimum range of alkalinity is 1500 and 5000 mg/L anaerobic digester.

2.4 Biogas:

Biogas is the mixture of gases released during the process anaerobic digestion of biodegradable substances under the action of Facultative and obligatory anaerobic bacteria. Biogas mainly comprises of methane in the range of 50-75 % of methane by volume, up to 25-50 % of CO_2, 0-10 % N_2, 0-1 % H_2, and 0-3 % H_2S [12]. The following table shows the typical properties of biogas.

Table 2.1 Properties of biogas:

S No	Property	Value
1	Energy Content	6-6.5 kWh/m^3 20 MJ/m^3
2	Fuel Equivalent	0.6-0.65 l oil (0.57 LPG)/ m^3 biogas
3	Explosion Limits	6-12 % biogas in air
4	Ignition Temperature	650-750 ^oC
5	Critical Pressure	75-89 bar
6	Critical temperature	-82.5 ^oC
7	Normal Density	1.2 kg/ m^3
8	Smell	Odourless at low H_2S
9	Combustion efficiency	60 % in stoves
10	Effective molecular weight	20.1 to 25.9

2.4.1 Applications:

Recent applications include fuel as substitute of firewood, LPG, petrol, diesel. It is also used to fuel the combined heat cycle power plants, and to supply natural gas grids.

2.4.2 Advantages:

1. Manufacture of nutrient rich soil conditioner and a very good organic fertilizer which is weed free if NISARGRUN design.
2. Balance of ecological cycle.
3. Micro economic benefits by fertilizer and energy substitutes.
4. Macro-economic benefits through decentralized energy production.
5. Reduction in waste deposition and disposal.

2.5 Aspen plus:

Aspen plus is the software created at Massachusetts Institute of Technology for simulating coal conversion process which was later developed to simulate most of the chemical plant processes. It is now one of the versatile and powerful tool to model the energy production and chemical unit operations as well as unit processes or the combination of any. The software contains a model library where most of the typical chemical unit processes could be found. Apart from that, it has a source with a large list with data of chemical compounds for using it in the simulation. If special process or special chemical compound data is not found in the data bank, it can be incorporated using the user defined databanks.

2.6 Anaerobic digestion models:

Some valuable models exist for replicating the biodegradation of complex natural substrates. In the majority of those models, the substrates are considered to be made of proteins, lipids and carbohydrates, where a few inhibitions are taken in record and some models do specially focus on the degradation of lingo-cellulosic biomass. Others models focus on general design parameters of the biogas plant.

The present model used in our study is the modified process simulation model which has the hydrolysis reactor modelled based on the extent of reaction, acidogenesis is modelled in the R CSTR and Acetogenesis and Methanogenesis are separately modelled in another R CSTR. The property data required for various amino acids were provided form the collections of Roger perris et al. [12] and Karthik Rajendran et al. [27].

Chapter 3

LITERATURE REVIEW

Survey on conventional digester designs:

3.1 Single stage digesters:

3.1.1 Fixed dome digesters:

An initiative by China and introduced in India as JANTA model which was re launched with certain leak proof modifications as DEENBANDHU model and presently recommended as simplified hemi spherical dome shaped CAMARTEC model. It is installed underground with feed inlet and outlet on the ground level. Dome is projected above ground which has gas outlet valve. It has a life span of 20 years minimum with regular and periodical maintenance and a capacity that is versatile in the range of 5 to 200 cubic meters [30]. It has disadvantages of difficulty in construction and perfect coating for gas proof is required. Also substantial fluctuation in gas pressure is observed which makes it less preferable.

3.1.2 Floating dome digester:

Moving gas holder is an inverted drum suspended in the upright digester containing slurry which acts as liquid seal. Drum movement depicts the production and consumption of gas. Medium scale production is recommended for the capacity of 5-15 cubic m digester and large operation at 50 -200 cubic meters [30]. KVIC model, a cylindrical digester is the oldest floating drum model. The same configuration with hemispherical dome is known as PRAGATI model. Ganesh model is another design which runs on same principle but has dome made of plastic foil and angular steel. BORDA model combines the static advantages of hemispherical digester along with the process-stability of the floating-drum and longer life span of water jacket plant. This design poses major disadvantages of higher installation costs, difficulties in maintenance and clogging is encountered due to scum formation reducing the free movement of gas holder inside the digester which requires frequent monitored cleaning in case of operation with fibrous feed stocks.

3.1.3 Balloon Plants:

Balloon plants are another type of anaerobic digesters having heat sealed plastic flexible variable volume container as the gas collector. Gas pressure is manipulated by placing weight on balloon. Material has to be weather, UV resistance. It poses major disadvantages of short useful life span (2 to 5 years), difficulty in scum removal and identification of leaks. Continuous human intervention is required for acting on the repairs.

3.1.4 Horizontal digesters:

These digesters are installed above ground which are easier to maintain and attend the maintenance issues. The digester has more area of gas liquid contact which reduces the segregation of slurry into layers and also reduces the scum formation.

3.1.5 ARTI model:

This was invented with an objective of degrading mainly food waste rather than animal manure. The plant is suitable in urban households as well as rural households with the constructional parts readily available in market. The gas production is estimated to compensate for around 50 percent of LPG consumption in a family. The time for complete digestion in the digester is 40 to 72 hours and the ratio of waste to water into the digester is 1 to 1.5 kg waste : 15 L water.

3.2 Two stage anaerobic digester:

The two stage anaerobic digester consists of separate hydrolyser, acidogenesis reactor and methanogenic reactor. The substrate is treated at various HRT in the three reactors which reduced the combined overall HRT and thus increases the capacity. NISARGRUNA digester design invented by Dr Sharad Kale from BARC is the well-established and efficient two stage anaerobic digester configuration. The plant requires a space of nearly 50-60 cubic meters for the waste input capacity of 0.5 metric tonnes per day and has the acidogenic reactor at HRT of

4 days having 7 kinds of Bacillus bacterial strains performing the reactions. The methanogenic reactor can be operated at HRT of 11 and produces around 90 to 100 cubic meters of biogas with 70 to 75 % methane concentration per tonne of waste processed. The plant is versatile to the type of substrate and is widely implemented in Maharashtra [31] [32].

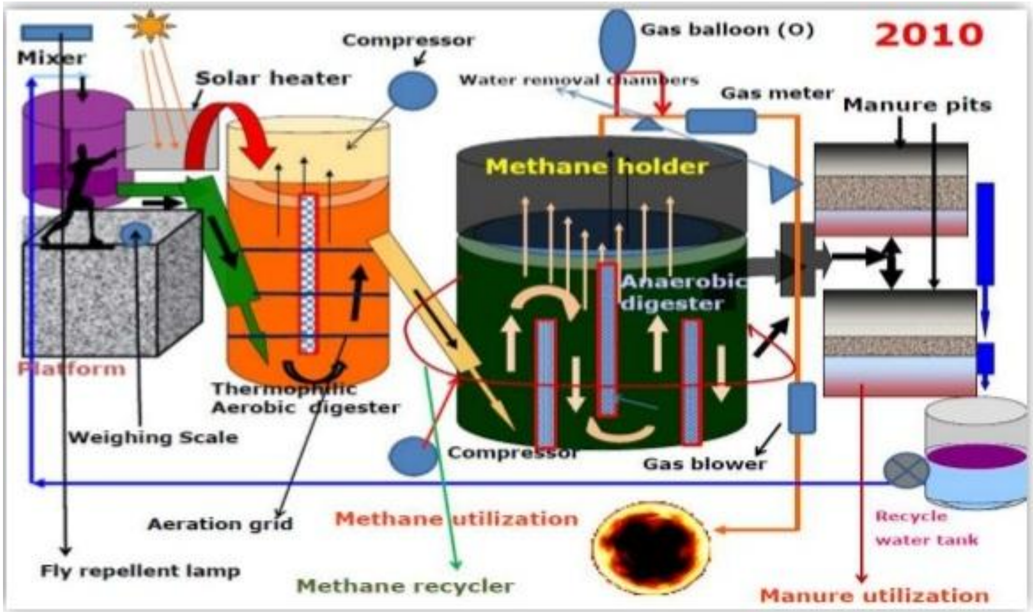

Fig. 3.1 Nisargruna plant flow diagram

3.3 Review on the experimental findings:

Nature and composition of the substrate, temperature, pH, OLR and HRT significantly affects the biogas production and degree of digestion in the anaerobic reactor. P. Vishwanath et al. [1] used versatile and mixed form of substrates composing mixture of tomato, jack fruit, pineapple wastes, orange peels with oil in various proportions in pilot scale studies at 60 liters capacity for various HRTs in the range of 8-24 days, TS content in the range 4-10 % by mass/volume of and obtained the biogas yield of 0.6 l/g VS added with maximum concentration of 59% methane by volume. In his work critical observation was that 60% of the total gas production was within first 12 hours of feeding. B Velmurgan et al. [2] used fruit and vegetable wastes such as banana stem, ladies finger, cabbage in 2 L scale using inoculums from bio methane plant at

Chennai for OLR 2.25 kg VS/ $m^{-3}day^{-1}$ and recorded 0.595 (L/g of VS added) biogas with 65% methane concentration. H. Bouallagui et al.[3] used tubular reactor (18 L) for treating arbitrary fruit and vegetable wastes using OLR 4 -5 kg VS/ $m^{-3}day^{-1}$, HRT 20 days and 6 % TS content and obtained 0.69 (L/g of VS added) biogas. The degradation efficiency was 75 %. Azadeh babaee et al. [4] conducted pilot plant study in 70 L scale on degradation of vegetable waste at 25 days HRT and by varying OLR in the range 1.4 -2.75 kg VS $m^{-3}day^{-1}$ and recorded biogas production of 0.396 L/g VS added with 65 % methane concentration. Imalfa et al. [5] studied the biogas production in batch digestion from the substrates of pre-treated cow dung, lemon grass and poultry manure which gave highest average biogas production of 7.3 L/day. Jin Young-Jung et al. [13] experimented on piggy waste for anaerobic digestion in a pilot plant scale and observed an average methane production of 0.32 m^3 CH4/kg COD removed in a two stage process. T Subramani et al [22] showed that biogas production is 0.465 L/g VS day for the aerobically pre-treated waste which was greater than that obtained from the digestion of untreated waste which gave 275 ml/g VS supplement. In the same work, municipal solid waste and sewage sludge showed the VS reduction of 41.1 percent without pre-treatment and 57.2 percent with pre- treatment.

3.4 Review on substrate compositions:

3.4.1 Poultry manure compositions:

Poultry manure from layer farming is mostly composed of around 78 % moisture [16] and the remaining of it is total solids out of which is only 64 percent is the volatile solid composition and remaining is considered as inorganic ash. It has the density of around 960 kg/cubic meters and has high ammonia content leading to pH of nearly 8.4 [16].

3.4.2 Kitchen waste composition:

The kitchen waste has high potential for biogas generation because most of the cooked constituents being hydrolysed to the maximum extent. So the substrate is easily digestible and it also has the pH in the acidic range suitable for direct feeding to acidogenic reactor after proper mixing with process water stream. Typical content of the kitchen waste were referred from the collections of A. R. Tembhurkar et al. [34] which portray that the disposal from NIT Nagpur mess contains cooked rice in the range of 23 to 59 %, cereals in the range of 8.76 to 18.93 %, cooked veg 5.68 to 16.72, chapatti – 18.67 to 41.9 and vegetable waste in the range 17.4 to 29.5.

3.4.3 Cow manure compositions:

Cow manure was assumed to be containing around 88 percent moisture [39], [40] and the remaining 12 percent was assumed to be of total solids out of which 82.5 percent are the volatile solids. The total solid content can be further classified into 52.6 percent fibres which has 13 percent lignin, 27.4 percent cellulose and 12.2 percent hemi cellulose [33].

3.5 Review on anaerobic digestion models:

3.5.1 Anaerobic digestion model number 1 (ADM 1):

The model incorporates exchange about biochemical and physio-chemical responses structure. Crumbling, Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis steps are incorporated in the model structure. Additionally, biochemical energy information network is given. Crumbling and hydrolysis are incorporated as additional cell solubiliztaion steps. Where crumbling is generally no-natural step that changes over biomass particulate to inactive sugar, protein and lipids; and where hydrolysis (enzymatic) changes over particulate sugars, proteins and lipids to monosacharides, amino-acids and long chain unsaturated fats, individually. Both courses of action are depicted through first request energy, where deterioration is utilized to portray biomass particulate material corruption, and where hydrolysis is utilized to depict all around characterized unadulterated substrates.

Data for the usage of the model in constant stream mixed tank reactor framework is incorporated with information in the indices. Monosaccharide and protein debasement to blended natural acids, hydrogen and carbon dioxide is performed with two gatherings of acidogens. Acetogenic gatherings change over natural acids, (for example, long chain unsaturated fats, butyrate, valerate and propionate) to acetic acid derivation, carbon dioxide and hydrogen, which is devoured by a hydrogen-using methanogenic gathering while acetic acid derivation is devoured by aceticlastic methanogenic gathering. As a premise for all the intracellular responses, substrate-based uptake monod-sort energy is utilized. Death of biomass was considered to occur by first order kinetics, which is kept up in the framework as a solid phase material because of it is thought to be not solvent soluble.

Inhibition due to pH influences all groups, hydrogen influences acetogenic group of digesting bacteria and free ammonia inhibits acetoclastic methanogens. pH inhibition was considered to be an empirical equation, while no-competitive inhibition function represent hydrogen and ammonia inhibition. Other than secondary monod dynamic inhibition functions were utilized to constraint growth when nitrogen is the limiting reactant and to keep the aggressive uptake of butyrate and valerate. Acid-base reactions and also non-equilibrium liquid-gas transfer were the mechanisms utilized to depict the physical and chemical procedures.

3.5.2 Process simulation model:

Process simulation model was developed by Karthik Rajendran et al. [27] to study the biogas production kinetics using aspen plus. The PSM is a library model of anaerobic absorption, which predicts the biogas creation from any substrate at any given procedure condition. A sum of 46 reactions were utilized as a part of the model, which incorporate inhibitions, rate-kinetics, pH, ammonia, volume, loading rate, and retention time. The hydrolysis reactions were considered based on the extent of the reaction, while the acidogenic, acetogenic, and methanogenic reactions were considered based on the reaction kinetics.

Chapter 4

Auto mix Single Stage Digester

Part 1 Experiments and Trails

The chapter explains the initial adapted changes in the digester construction as a form of preliminary design which was constructed and made operational to test for the feasibility in two trails one in 20 L scale and the other in 50 L scale one after the other. The final design was next explained with the procedure involving parameters fixation and the sequential steps of the auto mix cycle operation.

4.1 Preliminary Design:

The initial digester design incorporated following changes which include the use of 'U' shaped inlet for discharging the input substrate at the slurry surface in the digester and 'L' shaped outlet at the bottom of the digester as shown in the figure 4.1 which is a provision for collecting the sludge at the same level of inlet feeding.

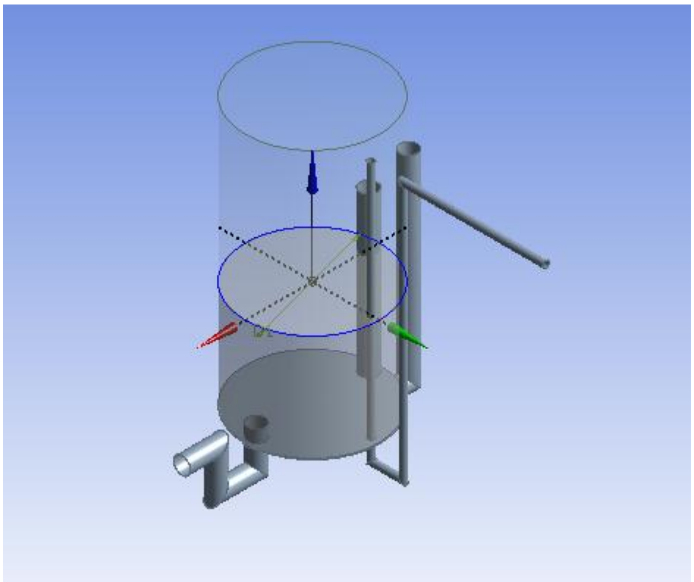

Fig. 4.1 Initial design of the digester configuration

The digester gas collector setup was first tested in 20L scale which lead to the modifications in the design and it was later implemented in 50 L scale that lead to our final design.

4.2 Feasibility Trail 1-20 L setup:

4.2.1 Construction and operation:

Transparent digester gas collector setup which was pipe sealed everywhere except at one bottom joint so that when the 1 ½ inch diameters PVC pipe is removed at that particular joint. It will act as sludge outlet when the pipe is removed and when it is closed back, it can act as slurry inlet. Gas outlet pipe is made out through the sealed bottom and introduced into the transparent container of 10 litres capacity which was inverted into the bucket of 15 litres capacity already filled with water. Weights were introduced on the inverted gas collector to maintain the rigidity of the assembly. Cow dung was made into slurry by mixing with water in the 1:1 (v/v) proportion. Slurry of 16 litres was fed to the digester and observed for batch production. The slurry was retained for 10 days and was observed for its operational feasibility and noting the technical difficulties to be encountered. Every day, gas production was observed by the overflow of water from the bucket as well as the rise of slurry level inside the feed pipe. The setup was intentionally made to be transparent to clearly observe the phenomena of scum formation and the zones of settlement. Due to the availability of light, methane production was very slow initially which took 10 days for the gas collected to attain flammability.

Fig. 4.2 20 L Digester experimental setup

4.2.2 Observations:

Gas production was observed from the second day of loading and was rapid during the day time and low during the nights. Amount of water overflow from the digester increased with increase in number of days during initial period of HRT and finally started to get reduced with time. Intermittent aeration was provided after 4 days of HRT and the gas production was notably good compared to that observed in the previous day. Initially aberrations were observed in the flame followed by instant put off from 5th day stating considerable carbon dioxide fraction. Bluishness in the flame followed by instant termination was observed from 6th day to 8th day which signifies increased methane concentrations. On 9th day, intensity of bluishness improved followed by stabilization was observed on increasing the flow rate of gas.

4.2.3 Practical difficulties and operational constraints:

Clogging was the most significant difficulty observed in the design which had resulted due to the sedimentation and the pipe diameter was not sufficient to for the free passage of thickened sludge. This urged for increasing the inlet and outlet pipe diameters for the next design. Gas deposition at the top of the slurry surface was not much satisfactory because of the entrapment of the gas in the form of the packets of significant size. This entrapment used to reduce the density of dung due to which development of three zones resulted such as Thickened zone: bottom thick sludge, Clarified zone: water with dissolved solids and Top zone: some dung used to rise above the water because it used to contain entrapped biogas in it due to which the overall density of the dung-gas mixture was found to be reduced to below that of water with dissolved solids.

4.2.4 Solutions and Recommendations:

As per the observations, it is recommended to have proper mixing to prevent clogging. Reducing the density of the feed inlet could lower the frequency of formation of the third layer.

Also increase in the cross section of the digester can significantly reduce the problems related to the gas entrapment.

4.3 Feasibility trail 2- 50 L Digester setup:

4.3.1 Construction:

In the experiments, 50 L digester setup with 45 L slurry working volume was used. The digester was an inverted vessel having provision for an inlet 'U' shaped 4 inch ID pipe as shown in the figure 4.4 which has longer arm outside the digester while the shorter end was projected inside towards the top end. Another 4 inch pipe takes a U turn from the tank bottom which was provided to act as an outlet to the digester. Pipe of size (1 or ¾ or ½ inch) has been considered based on the required rigidity which in turn depends on the length of pipe required inside the digester. The pipe was used to transfer the accumulated gas on the surface of the liquid in the digester to the separate gas collector. Pipe was introduced from the bottom in order to reduce the efforts of making the dome top as gas proof. Instead the bottom was made liquid sealed which was much simpler. This also reduces the wear and tear of the digester wall due to the fluctuations achieved in the pressure of the gas inside the container.

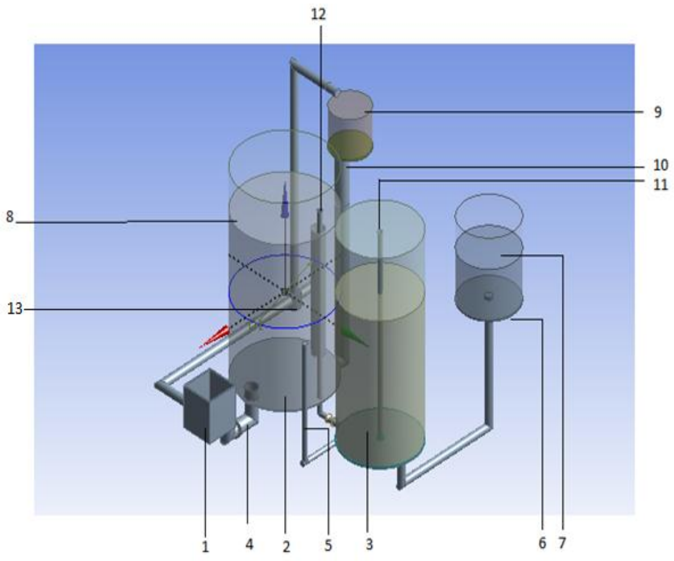

Fig. 4.3 Designed experimental setup for 50 L scale

1 - Mixing tank, 2- Digester, 3- Gas collector, 4- Sludge outlet, 5- Gas sample to the burner, 6- Siphon tank, 7- water level, 8- Slurry level, 9- Reactor siphon, 10- Feed inlet pipe, 11- Gas inlet to the collector, 12- Gas outlet and 13- slurry pump.

Fig. 4.4 Constructed Experimental setup (50 L)

4.3.2 Working:

Feed was introduced into the mixing tank where it encounters a part of underflow sludge from the reactor outlet and was fed to the digester. Sample of the outlet sludge was periodically taken to monitor the parameters such as VS, pH, temperature etc. Gas produced above the slurry level was passed to the gas collector on opening the gas valve while keeping the slurry and sludge valves closed which pushes down the water level in the gas collector down due to which water was displaced into the siphon tank through the connecting tube. Required pressure of outlet gas without disturbing the pressure of the reactor can be achieved by closing the valve V1 and simultaneously maintaining corresponding level of water in the siphon tank and then opening the remaining gas valves. Siphon tank was calibrated to know the amount of water collected in it periodically and adding corresponding water head to obtain the volume gives periodical gas production. If periodical mixing of the constituents are required, then closing all gas valves and simultaneously opening outlet sludge valve, results in the bottom denser sludge to be collected in the mixing tank, this was subsequently pumped to the feed introducing tank. This denser slurry was introduced at the top of the slurry surface by overflowing through the u shaped feed inlet pipe which makes the slurry inter mixing simplified compared to the conventional digester designs.

4.3.3 Inoculum

Self-inoculating system was developed using cow dung slurry (4:5 by volume in water) as mixed microbial culture by maintaining it for 10 days in the anaerobic and mesophilic conditions. During the time, batch performance of the digester for biogas production was conducted. When pH was consistent after 10 days, digester itself was used for conducting semi continuous study on vegetable wastes.

4.3.4 Analytical methods:

pH was measured using microcontroller Bench top (Systronics 9101 ATC). Temperature was measured using thermometer by sampling at various levels. Total solids (TS) and volatile solids (VS) were estimated using the methods proposed for waste water treatment [20]. Gas production was observed by the rise of liquid level in the siphon of gas collector. The height recorded in the siphon was liquid displaced by the occupied gas which in turn gives pressure in the gas collector. The excess volume of the liquid in the siphon gives volume change in the gas collector. Applying ideal gas assumption, the change in quantity of gas produced at any time was obtained.

4.3.4 Feed stocks and properties:

Cow dung was used alone for the preparation of digestion inoculum during batch study. Tomato wastes of the following properties as shown in the table (Table 4.1) were studied for anaerobic digestion during semi continuous study.

Table 4.1 Typical substrate compositions used

Parameter	Cow Dung	Tomato waste
Moisture content (%	86.48	73.665
Total Solids (% w/w)	13.52	26.33
Volatile Solids (%)	81.71	94.68
pH	7.1	4.6
Temperature ^{o}C	30	30

4.3.5 Physical Observations:

Advantages:

Due to the enhanced cross sectional area, the bubble entrapment has been reduced. The construction has been supporting the vertical mixing without wear and tear as well as the elimination of interruption in the gas holding space. No choking problems have been encountered in the 45 days retention without much vertical mixing, although the sediment sludge at the end of digestion has the solid content of nearly 15 % by mass. Perfect gas seal and reactor-collector communication have been observed and the assembly showed convenience for efficient mixing.

Disadvantages:

Manual mixing was difficult than expected. Fungal growth has been observed in the open spaces.

4.4 Experimental results:

4.4.1 pH variation:

pH is one of the most influential parameter in biogas production. pH in an anaerobic digester is the balance of competitive effect of production of VFA that was responsible for acidic nature and production of free ammonia and hydroxyl ions are responsible for basic nature. Higher pH > 7.6 would inhibit methanogenic activity whereas lower pH < 6.3 would hamper biogas production. So balanced rates of production should maintain the necessary pH (6.5 to 7.6) [14] for the optimal activity of methanogens. Alkalinity of digester in the range 1500 and 5000 mg/L [15] would retain the self-buffering capacity of digester despite the disturbances in the input pH.

4.4.1.1 Batch experiment results:

During batch observations, pH was maintained in the optimal range of methanogens as shown in the figure (Fig. 4.5). During the ninth and 10th days of operation, pH was stably fluctuating in the neutral range. It may be described by attaining self-buffering capacity. Thus the digester operated in semi continual mode.

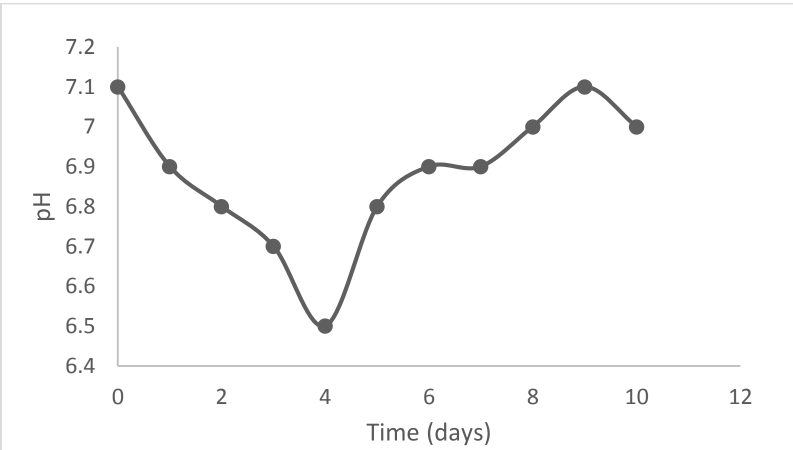

Fig.4.5. pH variation of digester slurry in batch process

4.4.1.2 Semi continuous experiment results:

During the semi continuous study, digester was fed with tomato waste of pH 4.3 and was operated at lower OLR of 1.6 Kg VS/m^3 day and sustained the pH change that was self-buffering (Fig. 4.6). pH drastically reduced to 5.7 when the operation was at OLR of 5 Kg VS/m^3 day and HRT was 16 days as shown in the figure.

Pallavi et al. [14] operated the thermally hydrolysed sludge in the mesophilic range 37-42 ^oC and SRT 15 and 20 days and the digester performed in pH 6.5 -7.0 in the first 30 days of operation. Alkaline treatment enhanced the pH and was maintained in the optimal range for the remaining days of experiment.

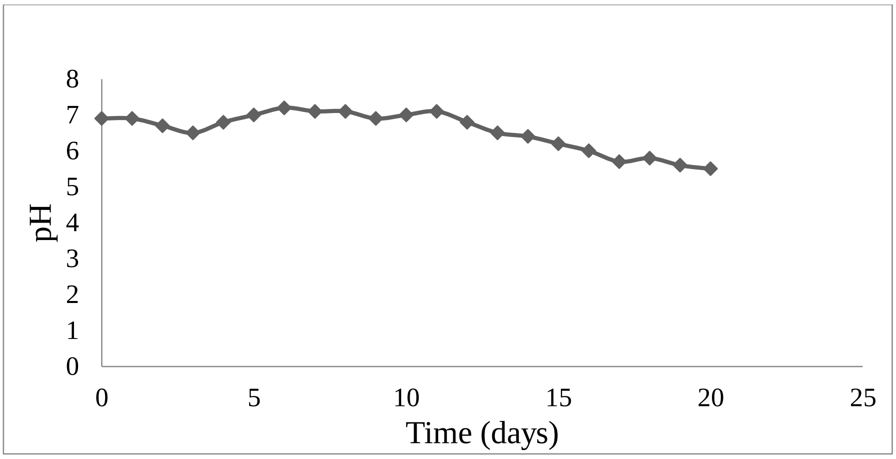

Fig. 4.6. Change in pH of the digester slurry with time in semi continuous process

Thus pH control during digestion process were reported often reported by many researchers. Jin-Young Jung et al. [13] conducted two stage anaerobic digestion, and had to control the pH of acidogenic digester for maintenance in the range of 6-7 during the initial days of operation for enhanced gas production of s 0.32 m^3 CH_4/kg COD removed. Adrian et al. [17] studied the digestion of mixed agricultural wastes and wheat bran and observed the pH of 5-7 in the first 50 days of operation using wheat bran and 6-7 using mixed agricultural waste. A.E. Ghalay et al. [16] operated the digester in two stage process and observed for the effect of pH control, without any pH control he observed the operation of second stage digester reaching neutral pH in the initial stages of operation. However the pH lowered to below 4 in the 20^{th} day of operation.

4.4.2 Temperature variation:

Temperature was an important parameter influencing the digestion rate and efficiency. It also indicates the digestion progress in the reactor. Mesophilic digestion in the range of 30- 45 ^{o}C is easy and convenient to operate the anaerobic digester.

4.4.2.1 Batch experiment results:

In the batch reactor, temperature was recorded as shown in [Fig. 4.7]. The substrate temperature was 28 ^{o}C during the feeding and was consistently rising with time indicating the progress of anaerobic digestion which is exothermic process [18].

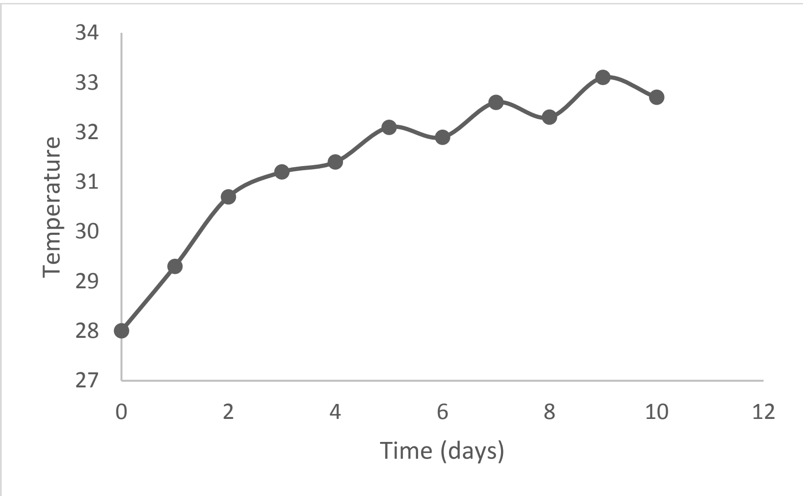

Fig. 4.7 Change in temperature of the digester slurry with time in batch process

4.4.2.2 Semi continuous experiment results:

During the semi continuous operation, temperature was fluctuating within 30 ^{o}C-34 ^{o}C and was highest in the second week of operation. Phenomenon can be explained as the increase in the digestion rate and gas production enhanced the reaction and hence temperature increased during first week of operation. However further increase in the substrate input increased VFA production rate compared to methanogen activity which resulted in the highest temperature record. But due to severe VFA accumulation from the end of second week along with increase in feed input at temperature 28 ^{o}C in combined effect led to lowering of temperature to 30 ^{o}C that signifies the VFA accumulation (Fig. 4.8).

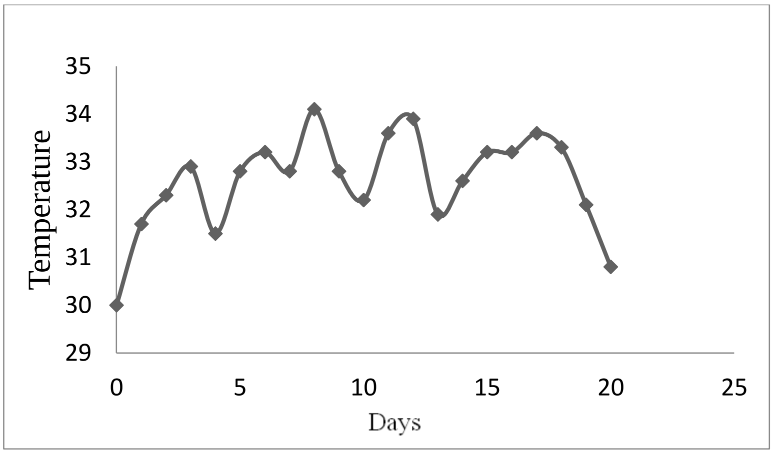

Fig.4.8 Change in temperature of the digester slurry with time in semi continuous process

A.E. Ghalay et al. [16] similarly conducted two stage digestion and observed the temperature fluctuations in the range 34 to 37 during 50 days of operation. Adrian et al [17] conducted the digestion of wheat bran and mixed agricultural waste and observed temperature to be varying in 30-40 ^{o}C and fall to below 30 ^{o}C after 50 days of operation.

4.4.3 Gas Production:

Biogas production was influenced by the factors such as HRT, OLR, VS concentration, Temperature and pH of the digester slurry. An optimum collection of parameters would maintain the balance in acedogenic, acetogenic and methanogenic activities and give good gas yield and higher methane concentrations.

4.4.3.1 Batch experiment results:

During the batch study, only cow dung was used as substrate with an objective to prepare self-inoculated system with self-buffering capacity. Figure [Fig. 4.9] illustrates change in gas production with time. Maximum production of 4.5 L was observed in the 8th day of installation [**Fig.** 4.9]. The production was stable thereafter and the digester was treated with tomato wastes for semi continuous study.

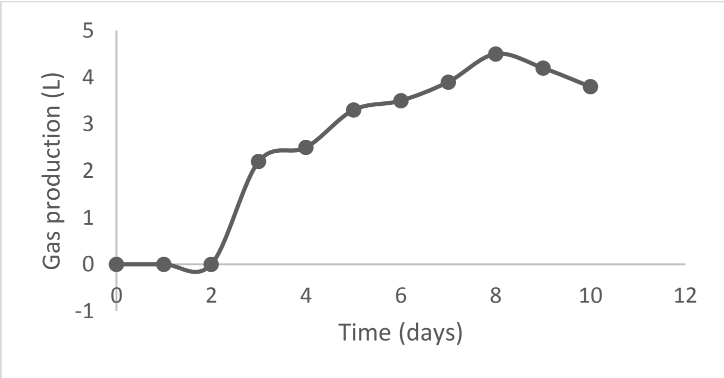

Fig. 4.9 Change in gas production with time in batch process

4.4.3.2 Semi continuous experiment results:

During the semi continuous study, the tomato wastes with pH 4.3 were subjected to anaerobic digestion for three weeks at different OLRs that resulted in gas production as shown in the figure 4.10.

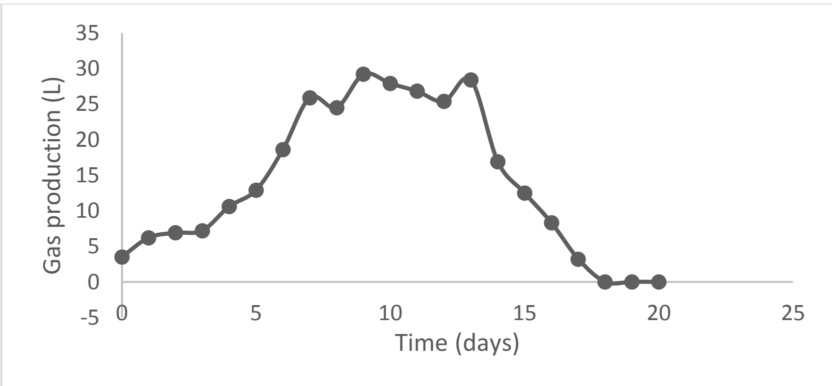

Fig. 4.10 Change in gas production with time in the semi continuous process

Table 4.2 Results summary of semi continuous run 50 L setup

Duration	HRT	OLR (Kg VS/m^3 day)	VS fraction (w/w)	Average gas production (L/day)	Specific production (L/g VS /day)
1^{st} Week	25	1.6	0.04	9.414	0.13
2^{nd} Week	20	3.5	0.07	26.87	0.17
3^{rd} Week	16	5	0.08	5.84	0.026

4.6 Discussion:

High OLR with pH 4.3 resulted in higher Volatile Fatty Acid accumulation and pH fell drastically to 5.8 on 18^{th} day of semi continuous operation. Gas production was entirely terminated and yet the digester was active which could be illustrated by the consistent temperatures above 30 ^{0}C in the digester even though the temperature of ambience reached 23-25 ^{0}C. Similar case has been illustrated in the experiments conducted by Berlian Setarous et al. [9] on 200 liters batch digester which has turned sour (pH < 6) after 3^{rd} week of installation and it got stabilized to neutral and attained self-buffering capacity after the 9^{th} week of installation.

4.7 Conclusion:

. As a part of work on single stage digester configuration, inability to intermittent mixing and aeration was considered as the problem statement and considered to design the digester configuration that could auto mix the digester constituents and simultaneously enhance gas production. For this purpose, a feasibility trail was conducted in a 20 L scale using cow dung as substrate. The physical observations for technical difficulties and operational constraints suggested the use of reactor siphon which was implemented in a 50 L scale. In this setup, experiments were performed in batch and cow dung as inoculating medium. The digester was next observed in a semi continuous mode for biogas production using tomato wastes at various HRT, Volatile Solid concentrations and OLR. Maximum specific gas production of 0.17 L/g VS/ day was noted during the second week of continuous operation and the digester turned acidic under heavy load of 5 OLR at 16 days HRT and 8 percent Volatile solid concentration. The studies signify that pH of the feed substrate not only influences the gas production and composition but also fixes the limits of operational parameters such as HRT and OLR. Thus using vegetable waste such as tomato waste, efficient biogas production can be achieved if optimum process conditions are maintained in a semi continuous digester.

Chapter 5

Auto mix Single Stage Digester

Part 2: Final design and parameter optimization

5.1 Digester Gas collector design:

This chapter explains the final design and sequential steps of operation for the digestion auto mixing process. The digester was modified by reducing non useful the length of reactor inlet as shown in the figure 5.1.

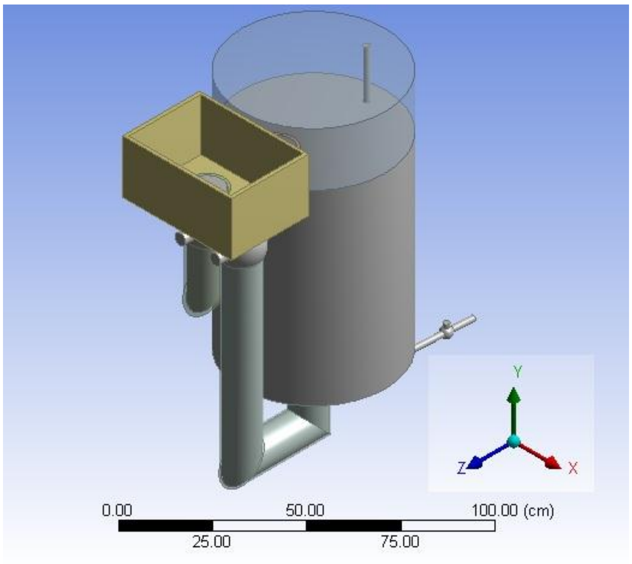

Fig 5.1 Single Stage Auto Mix anaerobic digester isometric view

Gas collector was added with a pressure neutralizer along with a pressure siphon in order to facilitate the operation by both mechanisms of natural mixing process as well as by the induced pressure driven mechanism.

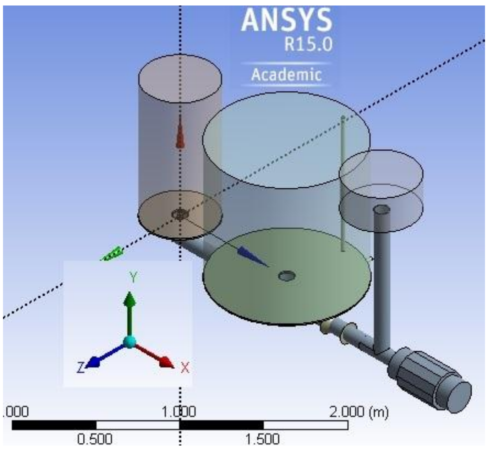

Fig 5.2 Gas collector design Isometric view

The following figure shows the flowchart of the combined reactor gas collector setup which explains the step by step procedure to operate the digester.

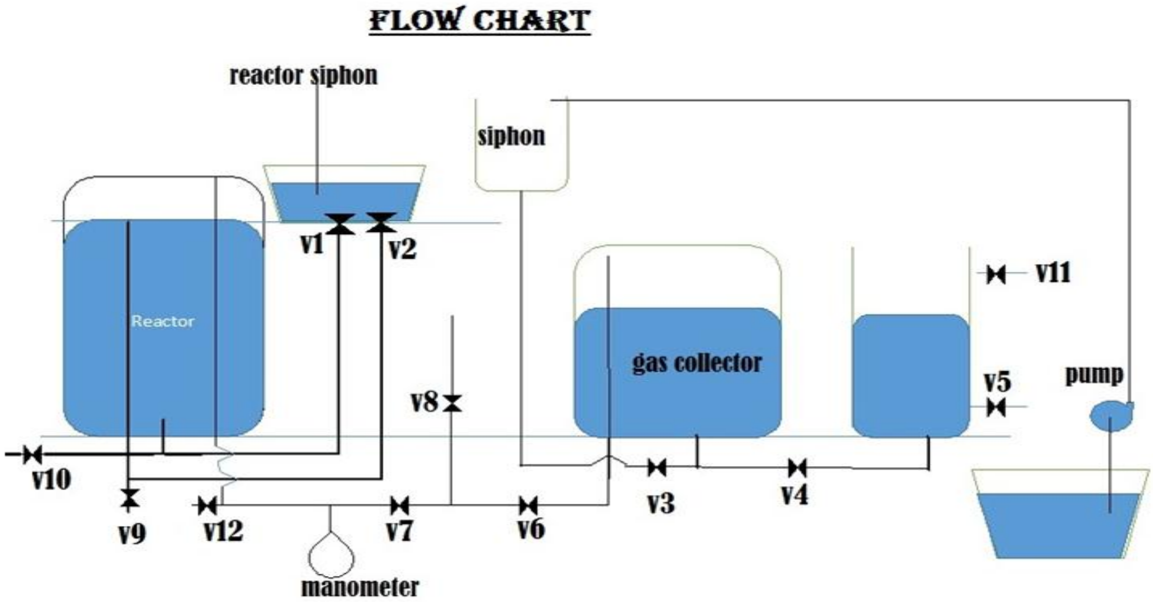

Fig 5.3 Flow sheet of the operational Auto mix configuration

5.2 Working:

Step 0:

Reactor is to be filled with the diluted substrate and the gas collector assembly is to be filled with water to the designed container levels and all valves are now closed after ensuring that pressure is 1 atm in the gas space of reactor as well as gas collector. Assembly is left undisturbed until the pressure in the reactor gas space reaches P_1 atm.

Step 1:

V1 is now opened keeping all other valves closed. This would result in the accumulation of slurry from the bottom of the digester in the reactor siphon. New equilibrium pressure is developed in the digester gas space which is to be denoted by P_2.

Step 2:

V1 is to be closed and simultaneously opening V2, V4, V6, V7 and V11. This would now push some of the substrate that was previously accumulated in the reactor siphon into the digester through its inlet which would reach top slurry level. After that equilibrium is reached at the pressure P_3 where $P_{atm} < P_3 < P_2$.

Step 3:

Now V2 and V4 are closed. Keeping V6 and V7 open, V1 and V3 are simultaneously open turning the pump on. Adding water through the siphon to the gas collector would rise the pressure in the collector followed by the reactor which results in the pushing of slurry from the outlet pipe into the reactor siphon through valve V2.

Step 4:

After attaining the sufficient level of slurry accumulation in the reactor siphon, V3 and V2 are closed simultaneously opening V1, V4 and V11which would repeat the cycle again pushing back slurry in the reactor siphon to the surface.

Pump used for water pumping has the circuit connected to the level indicator in the siphon. Thus when the level in the siphon reaches maximum value, pump gets switched off. A slight reduction in the water level of the siphon switches the pump on. When V3 is closed in step 4, water is filled to the maximum level in the siphon and pump turns off. While repeating the cycle again, from step 2, to push the gas in the reactor, net hydraulic head provided by siphon that of reactor siphon acts as driving force, and when the level of water in the siphon descends, pump automatically turns on.

5.3 Pressure relations:

Following equation relates the net volume of slurry that is recycled in **first cycle** after gas production and to the pressure attained in the reactor gas space **P_1**:

Equation 5.1:

$$2(V_2^R - V_0^R) = \sqrt{\left[\left\{V_0^R - \frac{A^{RS}\beta P_0}{(\beta+1)\rho_{sg}}\right\}^2 + \frac{A^{RS}\beta P_1 Z_2 T_2 V_0^R}{(\beta+1)\rho_{sg} Z_1 T_1}\right]} + V_0^R - \frac{A^{RS}\beta P_0}{(\beta+1)\rho_{sg}}$$

Where $\beta = (A^R - A^P)/ A^{RS}$

This gives height attained by slurry level in the reactor siphon $H^{RS} = (V_2^R - V_0^R)/A^{RS}$.

5.2.1 Terminology:

V_2^R = volume of the gas space in the reactor after step 1. V_0^R = initial volume of the gas space in the reactor. A^R = cross section area of the reactor. A^P = cross section area of the slurry inlet pipe. A^{RS}= cross section area of the reactor siphon. P_o = atmospheric pressure. ρ_s = slurry density. g = acceleration due to gravity. P_1 = pressure attained in the reactor gas space after step 1. Z_1 and Z_2 are the compressibility factors corresponding to temperatures T_1 and T_2 during step 1 and step 2 respectively.

5.4 Parameter optimization:

In the design, amount of pressure build up in the gas space, and ‘b’ the ratio of cross sectional area of the reactor siphon to that of reactor are the two interdependent operational parameters. The following discussion presets operational range of pressure for a particular value of b for a digester setup with 2000 L working volume.

Following figure 5.4 shows the variation of accumulated slurry in the reactor siphon with the value of b at various gas space pressures. Figure 5.5 shows the variation of percent of total slurry accumulated in the rector siphon for aeration with total gas space pressure in the digester.

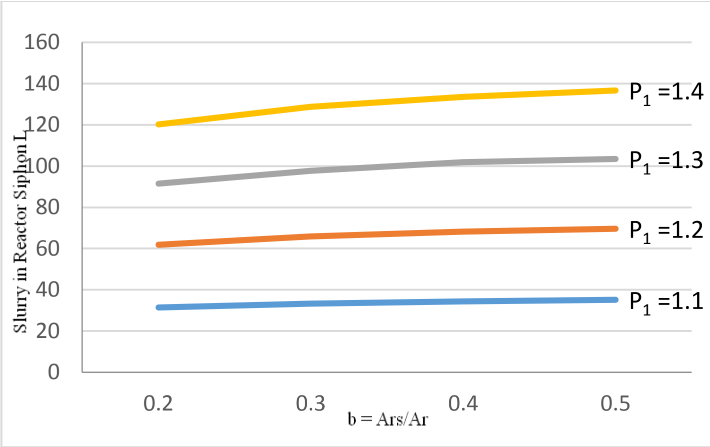

Fig. 5.4 Variation of slurry accumulation in Reactor Siphon with b

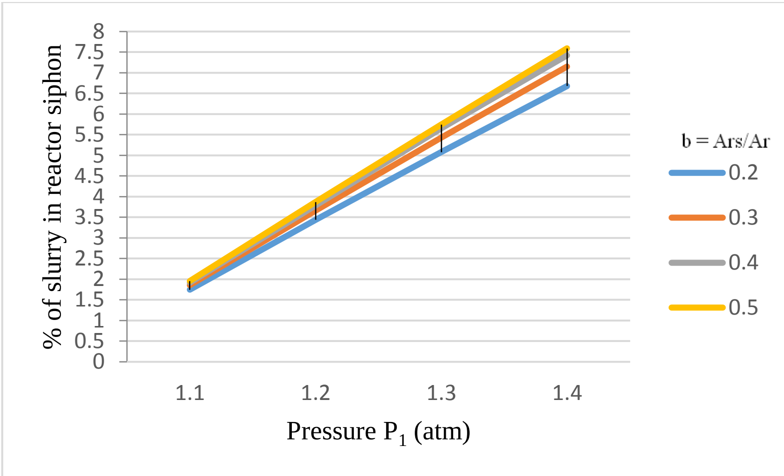

Fig. 5.5 Variation of slurry accumulation in Reactor Siphon with pressure P_1

The data clearly shows, with increase in the Reactor siphon cross section, there is not a much variation in the slurry accumulated in the reactor. For ease of construction and operation, reactor siphon with 0.2 Ars/Ar can be used at the pressure of 1.4 atm.

5.5 Code for the calculations:

```
#include<stdio.h>
#include<math.h>
#include<conio.h>
int main()
{
```

```
float Vr, d, a, Hr, Dr, Ap, Dp, b, Ars, c, sg, A, Pf, dPf;
float Ar;
double Drr, Dpp, dVv, dV;
int j, k;
char i;
for(j=1;j<20;j++)
{ printf("calculation of cross section area\n");
        printf("\n give the reactor volume and fraction of reactor volume for gas space in the decimals\n");
        scanf("%f %f", &Vr, &d);
        printf("\n we have Hr = Dr*a... give a\n");
scanf("%f", &a);
Drr= (1.273*Vr)/(a);
Dr = pow(Drr,0.3333);
Hr = 2.0*Dr;
Ar = Vr/Hr;
printf("\nreactor diameter is %f\n", Dr);
printf("\nreactor height is %f\n", Hr);
printf("\reactor cross section is %f\n", Ar);
printf("\n Calculation of pipe cross section'\n");
printf("\n give pipe diameter in inches\n");
scanf("%f", &Dp);
Dpp = Dp/4;
Ap = 0.008107*pow(Dpp,2.0);
printf("\n pipe cross section is %f", Ap);
printf("\n give specific gravity of slurry\n");
scanf("%f", &sg);
for(k=1;k<5;k++)
{ printf("\ncalculation of pressure drop\n");
printf("\n give absolute pressure in atm Pf\n");
scanf("%f", &Pf);
dPf = Pf-1.0;
```

```
printf("\n we have Ars = Ar*b... give b\n");
scanf("%f", &b);
Ars = b*Ar;
printf("\n Ars = %f \n", Ars);
c = (Ar-Ap)/Ars;
printf("\n c = %f \n", c);
printf("calculation of A\n");
A = Ars*(c*10.3297)/((c+1.0)*sg);
printf("\n Value of A is %f\n", A);
dVv = pow(((d*Vr)+A),2.0)+4*(A*d*dPf*Vr);
printf("\n dVv = %f \n", dVv);
dV = (pow(dVv,0.5)-((d*Vr)+A))/2.0;
printf("\n volume collected in the reactor siphon is %f\n",dV); }}}
```

5.6 Conclusion:

The ability of auto mixing mechanism is measured by the extent to which the amount of total slurry present in the digester is axially recycled. Conventional digesters have the production up to 1 cubic meters per cubic meter of the digester volume [1], [27]. So the effective mixing can be achieved by running the cycle under the pressure developed by the production alone (no power consumption cycle) and the pressure gradient obtained by water pump in the gas collector or water column based on the scale of operation.

Considering the above aspects, the amount of pressure to be developed in the gas space required to drive for the accumulation of a unit volume of the slurry in the reaction pump was calculated as shown by the equation 5.1 for various values. In the same study, percentage of the total digester slurry that can be accumulated in the reactor siphon was also studied for various operational parameters and the conditions were optimized for the particular scale (2000 L) of operation. These results and the mentioned code can give the optimum and set of operational parameters for any scale of single stage digester operation.

Chapter 6

Compartmental Digester:

Design and Experimentation

6.1 Compartmental digester:

The compartmental digester design is the evolved version of auto mix design configuration presented earlier which was design with an objective of suitability in the industrial operational scale. The digester has the added advantages of enhanced gas liquid interfacial area which would reduce the bubble entrapment without affecting the rates of sedimentation of solids inside the digester. This would also ease the mixing cycle and enhance the gas production. In the present design, the auto mix digester configuration was added with the secondary internal digester as shown in the figure 6.1

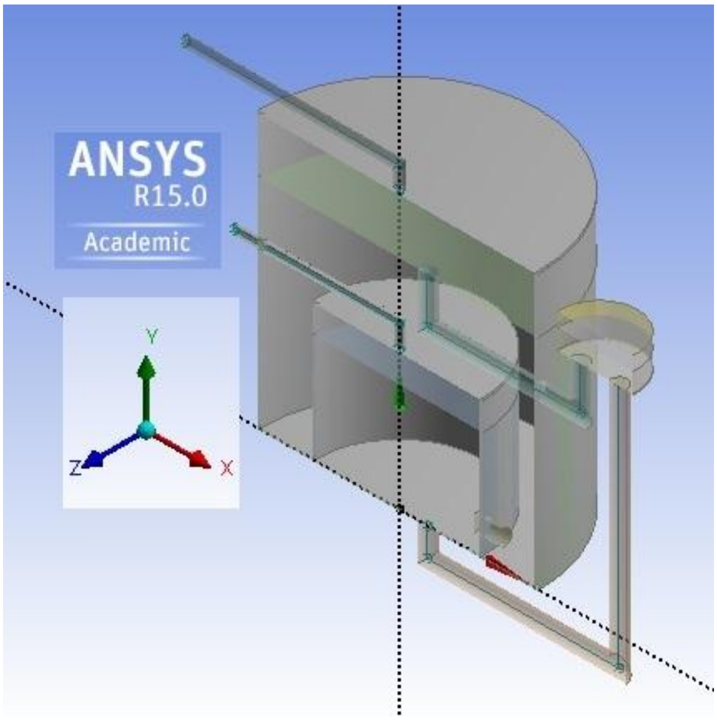

Fig. 6.1 Sectional view of the compartmental digester design

The initial design was constructed and operated in the scale of capacity 200 L to test the feasibility of the configuration. The experimental digester consisted of the an internal secondary digester having 50 L capacity which was operated in fixed dome manner, a 150 L primary digester which was operated in the floating drum manner and a separate 50 L horizontal digester of 50 L capacity for the comparison of results with that of internal digester.

6.2 Experimental setup

In this experiment, the advanced version of auto mix digester was designed using two digesters in configuration that one is embedded in the other. The digester has a 200 L HDPE barrel with open drum into which a 50 L digester was inverted and pivoted rigidly with added weight to sustain the upward thrust due to gas generation. The setup has the 4 inch inlet that will introduce feed to the bottom of the digester and the provision for sludge outlet at the top of the digester. Above the inner compartment, another 50 L container is inverted which will act as the unjacketed floating drum gas collector. Rise in the level of the vessel would give the approximate gas production in the top collector.

Fig. 6.2 Compartmental digester experimental setup

6.3 Results and discussion:

Table 6.1 Gas production obtained from the compartmental digester experimental setup

Day	Gas production L		
	Primary digester	Secondary digester	External digester
1.	5.2 Non flammable	9.0 Non flammable	6.5 Non flammable
2.	6.9 Non flammable	16.2 Non flammable	9.4 Non flammable
3.	15.9 Slightly flammable	23.6 Slightly flammable	16.5
4.	11.2	30.1	21.5
5.	18.2	27.9	23.1
6.	19.3	32.6	26.3

In this digester setup, the fed batch test was performed for a period of one week using the cow dung as substrate and mixed microbial culture. The gas production was monitored and the results were compared with the production obtained in each of the digesters. The configuration could not be run for many days because it was installed in the enclosed laboratory and dismantled quickly considering the possibilities of hazards due to the gas leakage.

Chapter 7

Simulation of Two Stage Anaerobic Digester

7.1 Simulation methods:

The process simulation model was modified by separately treating acedogenesis and combined acetogenesis and methanogenesis in the separate reactors. For this process, the property method NRTL was chosen for performing the simulation. The process models uses ten FORTRAN statement sets calculating the kinetics of various reactions for each iterative loop. Property data needed for the calculations were taken from the data collected and modified by Angediki et al. [26] and Karthik Rajendran et al. [27] and Roger Peris et al. [12]. The following figure shows the plant view of the simulation model using the kitchen waste as the substrate for digestion.

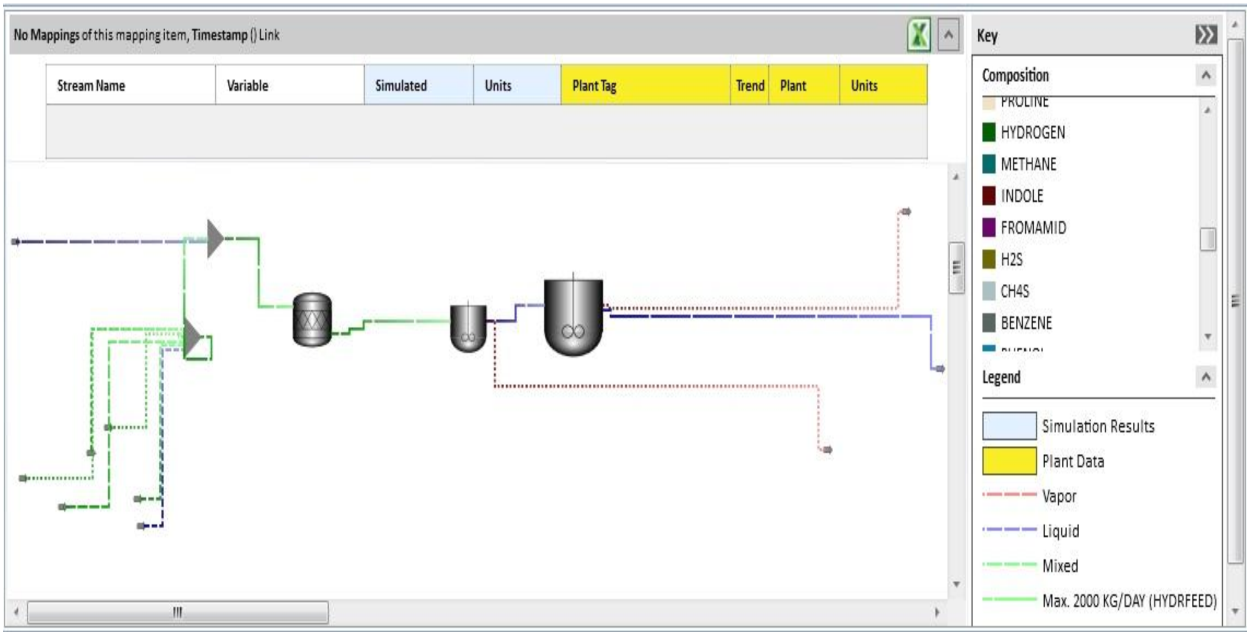

Fig 7.1 Simulation flow chart

7.2 Calculations of simulator inflow feed:

7.2.1 Calculations for kitchen waste simulator:

The base data regarding the limits and range to which a particular conventional substrate is present in the kitchen waste was obtained from the findings authors of VNIT Nagpur A. R. Temburkar et al [34]. From the data, the arbitrary set of the concentration of four varieties of foods such as cooked rice, cooked cereals, chapatti, cooked vegetables and raw vegetable waste was considered. The carrot and potato was considered in the vegetable stream.

Table 7.1 Composition of kitchen waste

S No	Substance	Range %	Considered value %	Reference
1	Cooked rice	23-59	40	A. R. Tembhurkar et al. [34]
2	Cereals	8.76-18.93	10	A. R. Tembhurkar et al. [34]
3	Cooked Vegetables	5.68-16.72	10	A. R. Tembhurkar et al. [34]
4	Chapatti	18.67-41.9	20	A. R. Tembhurkar et al. [34]
5	Vegetable waste	17.4-29.5	20	A. R. Tembhurkar et al. [34]

Table 7.2: Individual compositions

Substance	Protein	carbohydrates			fats	Moisture	Fibres	Inert	Sugars	Reference
	%	Cellulose	Hemi cellulose	Starch	%	%	%	Ash %		
Cooked rice	2	0.3	0.3	21.4	0.2	74.1	1	0.9		[37]
Cooked veg potatoes	1.8	1	0.6	13.4	0.04	80.42	1.8	0.65	0.29	[37]
Cooked carrot	0.69	1.0	0.6	1.3	0.22	91.8	0.69	0.42	1.2	[37]
Cereals	1.5	0.3		1.0	0.3	92.5	2.4	1.0	3	[37]
Chapatti	7.9	7.1	5	30	0	30.0	8	7	5	[36], [37]
Raw veg	1.8	1.2	1.2	2.4	0.4	88	3.5	0.75	0.75	[39]

Capacity of the plant: 1 tonne waste and 1 tonne process water

From the above data, after performing the process calculations, the following individual component stream were obtained.

Table 7.3 Feed inlet streams for kitchen waste in 1 ton capacity plant

Component Kgs/day	Cooked Cereal	Cooked Rice	Chapatti	Cooked potato	Cooked carrot	Raw veg waste
WATER	92.5	296.4	60	40.21	45	176
DEXTROSE	0.75		6	0.145	1	1.1
CELLULOSE	0.3	4.4	24.2	0.85	1.519	6
HEMECELL	0.24	1.2	18	0.85	0.5	5.8
GLUCOSE	0.75		2		0.25	0.2
TRIOLEIN	0.075	0.2	0.48	0.002	0.022	0.16
TRIPALM	0.075	0.2	0.48	0.002	0.022	0.16
PALM		0.04	0.02	0.013	0.001	0.16
SN-1--01	0.075	0.16	0.5	0.003	0.043	0.16
SN-1--02	0.075	0.16	0.5		0.021	0.16
XYLOSE	0.75		2		0.25	0.2
LINOLEIC		0.04	0.02		0.001	0
STARCH	1	85.6	60	6.7	0.8	4.8
PROTEIN	0.75	4	8	0.5	0.172	2
KERATIN	0.75	4	7.8	0.4	0.149	1.6
INERT	1.91	3.6	10	0.325	0.25	1.5

7.2.2 Constituents of Layer farming waste-poultry manure:

S. Chen et al [33] reported the complete content of fats, amino acids, proteins and carbohydrates in the poultry manure. The details were used in the simulator to note the biogas production. The poultry manure was considered to be containing approximately 78 % by weight of moisture and the remaining were assumed to be containing solids which are inorganics up to 19 % by mass on dry basis and remaining were considered to be organic solids.

Table 7.4: Stream input layer farm waste feed digester

Substrate		HISTIDIN	LYSINE	TYROSINE	TRYPTOPH	PHENYLAL
Inlet	Kg/day	0.462	1.364	0.726	0.22	1.166
Substrate		CYSTEINE	METHIONI	THREONIN	SERINE	LEUCINE
Inlet	Kg/day	0.682		1.298	1.188	
Substrate		ISOLEUCI	VALINE	GLUTAMIC	ASPARTIC	GLYCINE
Inlet	Kg/day	1.232	1.694	3.608	2.684	4.642
Substrate		PROLINE	CELLULOS	HEMECELL	TRIOLEIN	TRIPALM
Inlet	Kg/day	2.2	22	47.3	3.52	3.52
Substrate		PALM	SN-1--01	SN-1--02	XYLOSE	LINOLEIC
Inlet	Kg/day	0.88	3.3	3.52		
Substrate		ETHANOL	PROTEIN	KERATIN	INERT	STARCH
Inlet	Kg/day		4.4	54.56	41.294	12.54

The chicken manure with above composition was introduced into the simulator to find the rate of biogas production.

7.3 Results:

Table 7.5 Results of run 1 on kitchen waste

Biogas (308 K) Flow rate		Component Kg/day		Component Kmol/day		BARC biogas plant design (NISARGRUNA) specifications
M^3 /day	Kg/day	CO_2	CH_4	CO_2	CH_4	
78.346	70.985	31.646	35.159	0.719 Mole fraction is 0.23	2.192 Mole fraction is 0.707	90 -100 cubic meters with 70-75 percent methane content and 15 percent Carbon dioxide content [31].

Validation:

The process simulation model (PSM) developed by Karthik Rajendran et al. [27] was validated by the authors in various scales using various substrates from laboratory scale to that of pilot plant and large scales. In our model we being using the same set of equations with separate stage modelling gave us the results of the run as shown in the above table. The results when compared with that obtained from the existing design of BARC would show the lesser gas production by volume. But here, the mass flow rate of gas from the source of comparison and the simulated model meant to be almost same. This validates our model and the lesser volumetric flow rate is explained by the presence of the higher carbon dioxide and lesser methane content in the results of simulated model. This can be explained by the slower kinetics in the methanogenic stages and acetogenic stages of the simulated model compared to that of the BARC design which uses isolated and specific strains. The model kinetics were adapted using conventionally available data into consideration and hence these are to be further corrected considering the data of the BARC model.

Run 2 on poultry waste from layer farms:

Table 7.6: Results on poultry waste simulation

Biogas (308 K) Flow rate		Component Kg/day		Component Kmol/day	
M^3 /day	Kg/day	CO_2	CH_4	CO_2	CH_4
59.968	55.722	28.55	18.57	0.649 Mole fraction is 0.293	1.158 Mole fraction is 0.53

The lower gas production in terms of both mass as well as the volume can be explained by the variation in the substrate composition of the poultry wastes. Poultry waste has higher ash content and lower fraction of biodegradables compared to that of the kitchen waste. It is also at pH 8.4 (whereas the kitchen waste being at acidic pH nearer to 4) which is a disturbance stream to the acidogen reactor especially at HRT 4 operating at acidic pH. This is one of the reasons for the reduced gas production. Considering the fact that the kinetics of the simulation model being slower than that of the kinetics of the existing BARC model, the results obtained in this model can be considered to be the threshold value and can be taken as the minimum gas production rate and valid to be considered for energy and economic analysis calculations.

Chapter 8

Conclusion and Future work

The present work focused on the presented neglected problems of not incorporating mixing and intermittent aeration in the conventional methods of anaerobic digestion process in domestic scales of biogas production. The review on conventional digester designs lead to the basic design of the digester configuration that had undergone construction in a 20 L operational scale and was tested for feasibility. The cow dung was analysed for biodegradation during the trail and the transparency of the digester supported the observation of typical gas bubble entrapment phenomenon and the layer formation in the unmixed bio digester. The gas production increased initially followed by reduction and when subjected to intermittent aeration resulted in increase in the gas production. The suggested modifications in the design were incorporated in the form of 50 L digester gas collector setup. The test mainly focused on the observation of enhanced rates of attaining self-buffering capacity due to the effect of mixing and also tested the effect of intermittent aeration and mixing on the robustness of the digester exposed to extreme set of operational parameters. The digester was successful in operation up to 20 days of HRT. The final auto mix digester design

- Expected to have more efficiency of gas production which is enhanced due to continual mixing.
- Lower failure probability as the total gas collector boundary is immobile and indirect boundary in the form of water level always moves.
- Higher is the scale of operation, faster is the attainment of mixing cycle.
- Complete manual control and very ease of maintenance and replacement as no part is directly connected directly to the constituents that react thus replacing any component does not interact the process.
- Driving force for missing is supplied from water pump which is much cheaper compared to slurry pump and lot easier to maintain.

ARTI biogas digester design uses HRT of 42 days to compensate for the lack of internal mixing whereas the digester presented in this paper is observed to be stable at 24 Days HRT and thus gives more gas production. For the scales above 2 cubic meters of digester capacity, the water displacement gas collector can be replaced by balloon type collector with intermediate gas pressure regulating valve to give the same pressure swing and mixing effect.

Compartmental digester is the advanced design to the auto mix digester design which was tested for feasibility in 200 Litres operational scale and was observed to be feasible in large scales single stage applications.

The two stage anaerobic digestion was found to be more efficient for methane in both quantitative and qualitative production. The BARC-NISARGRUNA digester was attempted to be modelled as the modified process simulation model for studying the gas production kinetics in a. The kitchen waste with the calculated compositions from the data present in the literature was incorporated into the modified process simulation model developed as a part of the work. The results were validated with existing data and the model was then used to predict the gas production from poultry waste.

Future work:

The process parameters for the compartmental digester design has the optimized using computational fluid dynamics techniques. The same has to be analysed for stress and bending moments comparing the effect of incorporating the holes and joints at the roof. The compartmental digester design has to be implemented with applied instrumentation to automatize the mixing cycle.

The kinetics of BARC- NISARGRUNA digester has to be studied with experimentation which has to be used for corrections of the kinetics of the modified process simulation model.

References:

[1] PremaVishwanath (22-1991) "Anaerobic digestion of fruit and Vegetable waste for Biogas production" Biogas technology 40 (1992) 43-48

[2] Velmurgan (2011) "anaerobic digestion of vegetable waste for biogas production in a Fed-Batch reactor" Int. J. emergg. Sci. 1(3) 478-486.

[3] Bouallagui (2003) "Mesophilic biogas production from fruit and vegetable wastes in atubular reactor" Bio resource Tech.86 85-89.

[4] Azadeh Babee "Anaerobic digestion of vegetable wastes" School of petroleum engg. Tech. Iran

[5] IM Alfa (2014) "Comparison of evaluation of biogas production from poultry droppings, cow dung and lemon grass" Bio resource Technology 157 2014 270-277.

[6] Earnest Vinay Prakash (2013) "Biomethanation of vegetable and fruit wastes in co-digestion process" Int. J. emergg. Tech. and Adv. Engg. ISSN 2250-2459.

[7] Ukpai (2012) "Comparative study of biogas production from cowdung, cow pea, cassava peelings using 45 litres biogas digester" ISSN 0976-8610 AASRFC.

[8] Adebayo (2014) "Anaerobic digestion of cattle slurry with Maize stalk at mesophilic Temperature" e-ISSN 2320-0847.

[9] Berlian Sitorus (2013) "Biogas recovery from anaerobic digestion process of mixed fruit vegetable wastes". ICSEEA 2012 Energyopedia 32 (2013) 176-182.

[10] T G Narayani (2012) "Biogas production through mixed fruit waste Biodegradation" Vol. 71 March 2012 PP 217-220.

[11] Irini Angelidaki (2013) “Methods and apparatus for hydrogen based biogas upgrading” retrieved from http://www.google.com/patents/WO2013060331A1?cl=en Google patents WO2013060331 A1.

[12] Roger Peris Serrano (2011) “Biogas Process Simulation using Aspen Plus” Master Thesis, Department of Chemical Engineering, Biotechnology and Environmental Technology Syddansk Universitet.

[13] Jin Young-Jung (2000) “Effect of pH on Phase Separated Anaerobic Digestion” Biotechnol. Bioprocess Eng. 2000, 5: 456-459.

[14] Pallavi Bishnoi (2012) “EFFECTS OF THERMAL HYDROLYSIS PRE-TREATMENT ON ANAEROBIC DIGESTION OF SLUDGE” Master Thesis Virginia Polytechnic Institute and State University.

[15] Ken Schnaars (2012) “What every operator should know aboutanaerobic digestion” retrieved from OperatorsEssentials 82-33WWW.WEF.ORG/MAGAZINE.

[16] A. E. Ghalay (2000) “Effect of reseeding and pH controlon the performance of a two-stage mesophilic anaerobic digester operating on acid cheese whey” Canadian Agricultural Engineering Vol. 42, No. 4.

[17] Adrian (2012) “Comparative study on factors affecting anaerobic digestion of agricultural vegetable residues” Bio Technology for Bio fuels 10.1186/1754-6834-5-39 retrieved from http://www.biotechnologyforbiofuels.com/content/5/1/39.

[18] Gregor D (2012) “Anaerobic Treatment and Biogas Production from Organic Waste,Management of Organic Waste” ISBN: 978-953-307-925-7, InTech.

[19] V. NallathambiGunaseelan (2004) “Biochemical methane potential of fruits and vegetable solid waste feedstocks”Biomass and Bioenergy 26 (2004) 389 – 399.

[20] APHA, AWWA and WEF, “Standard methods for the examination of water and wastewater”, 20th edition, Washington D.C, 1998.

[21] Jagadish H Patil (2011) “A comparative study on anaerobic co-digestion of water hyacinth with poultry litter and cow dung”International Journal of Chemical Sciences and Applications ISSN 0976-2590. Vol 2, Issue 2, June-2011, pp 148-155.

[22] T Subramani (2012) “Anaerobic Digestion of Aerobic Pretreated Organic Waste” International Journal of Modern Engineering Research (IJMER) Vol.2, Issue.3, May-June 2012 pp-607-611 ISSN: 2249-6645.

[23] Anonymous (2014) “Country analysis brief overview” Independent statistics and analysis Retrieved from U S Energy Information Administration http://www.eia.gov/countries/country-data.cfm?fips=in.

[24] Ranjith karvel (2012) “Sustainable solid waste management in India” Master thesis Columbia University.

[25] N S Ramnath (2012) “Garbage generated around the world” Retrieved from Frobes India magazine http://forbesindia.com/printcontent/33226

[26] Angelidaki, I., Ellegaard, L., & Ahring, B. K. 1999. A comprehensive model of anaerobic bioconversion of complex substrates to biogas. Biotechnology and Bioengineering, 63(3): 363-372.

[27] Karthik Rajendran (2014) “A Novel Process Simulation Model (PSM) for Anaerobic Digestion Using Aspen Plus” S0960-8524(14)00076-5 Bioresource Technology.

[28] Anonymous Food and Agricultural organization United Nations “A short historical background on anaerobic digestion” Retrieved from http://www.fao.org/ docrep/t0541e /T0541E04.htm

[29] Y. VOEGELI (2009) "TECHNICAL AND BIOLOGICAL PERFORMANCE OF THE ARTI COMPACT BIOGAS PLANT FOR KITCHEN WASTE - CASE STUDY FROM TANZANIA" Twelfth International Waste Management and Landfill Symposium CISA Publisher, Italy

[30] Anonymous "Types of Biogas plants" retrieved from www.sgpindia.org/documents/ Biogas_plants.pdf

[31] Anonymous "NISARGRUNA Biogas plant based on Biodegradable waste resource" retrieved from http://www.barc.gov.in/technologies/kitchen/kitchen_br.html

[32] Priyavadhan Shah (2006) "Sustainable waste processing in Mumbai using Nisargruna Technology" Hogskolan I Boras Institutionen Ingenjorshogskolan

[33] S.Chen (2003) "Value added chemicals from animal manure" Washington state University for the U S Department of energy under contract DE-AC06-76RL01830.

[34] A. R. Temburkar (2008) "Studies of Hydrolysis and Acidogenesis of kitchen waste in a two phase anaerobic digester" Journal of IPHE India Volume 2007-2008 number 2.

[35] G Venkateswara Rao (1986) "Changes in quality characteristic of chapatti during storage" Cereal Chem. 63 (2): 131 – 135.

[36] Anonymous "Calories in chapatti" retrieved from http://www.sparkpeople.com/calories-in.asp?food=chapati.

[37] Throne M. Carpenter (1940) "COMPOSITION OF SOME COMMON FOODS WITH RESPECT TO THE CARBOHYDEATE CONTENT" The journal of nutrition, 1940 Vol. 19 No. 5.

[38] M Wadha (2013) "Utilization of fruit and vegetable waste as livestock feed and as a substrates for the generation of other value added products" RAP Publication 2013/04.

[39] Anonymous (May 2011) "Biogas Energy Potential in Alberta". Agdex 768-3

[40] Anonymous "Manure Production and Characteristics". ASAE D384.1 FEB03