ABSTRACT

INTELLIGENT PROCESS CONTROL FOR UASB REACTORS

by
Sita Mohan

The Upflow Anaerobic Sludge Blanket (UASB) reactor is widely used for the anaerobic treatment of concentrated municipal / industrial wastewaters and sludges. Ability to handle high organic loading rates and cost effectiveness are often the most cited merits of the UASB process. Numerous mathematical models have been developed to describe the process and mechanistic phenomena in these systems. However, evidence in the literature of these models having been applied, either as control or diagnostic tools is limited. The use of intelligent process control mechanisms can greatly ease problems associated with operating these reactor systems.

The objective of this study is to develop a Human Machine Interface (HMI) module to assist UASB operators to optimize process conditions based on input from transducers, analytical data and a knowledgebase. The module makes extensive use of algorithms developed for modeling UASB systems in evaluation of reactor performance. The module is part of an intelligent process control software which uses information from sensors monitoring process parameters in real time, analytical laboratory data and historical databases to make process adjustments automatically and advise operators on current process conditions and corrective action if necessary. It is expected that the HMI developed will result in improved operational stability by providing a better understanding of process parameters and their implication in optimally operating UASB reactor under steady state conditions.

INTELLIGENT PROCESS CONTROL FOR UASB REACTORS

by
Sita Mohan

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Environmental Engineering

Department of Civil and Environmental Engineering

January 2000

APPROVAL PAGE

INTELLIGENT PROCESS CONTROL FOR UASB REACTORS

by
Sita Mohan

Dr. Sudhi Mukherjee, Thesis Advisor — Date
Research Professor of Civil and Environmental Engineering
New Jersey Institute of Technology

Dr. Hsin-Neng Hsieh, Committee Member — Date
Professor of Civil and Environmental Engineering
New Jersey Institute of Technology

Dr. Taha Farouk Marhaba, Committee Member — Date
Assistant Professor of Civil and Environmental Engineering
New Jersey Institute of Technology

BIOGRAPHICAL SKETCH

Author: Sita Mohan

Degree: Master of Science in Environmental Engineering

Date: January 2000

Undergraduate and Graduate Education:

- Master of Science in Environmental Engineering
  New Jersey Institute of Technology, Newark, NJ, 2000

- Master of Housing,
  College of Engineering, Thiruvanathapuram, Kerala, India, 1993

- Bachelor of Civil Engineering,
  Government College of Engineering, Kannur, Kerala, India, 1991

Major: Environmental Engineering

ACKNOWLEDGEMENT

The author is deeply grateful to her thesis advisor, Dr. Sudhi Mukherjee for his guidance and encouragement. She wishes to express her gratitude to her thesis committee members, Dr. Hsin-Neng Hsieh and Dr. Taha Farouk Marhaba for their time and valuable suggestions. Further, the author is thankful to her friends for their help in the thesis work. She is very thankful to her husband, Manoj for his patience and invaluable help.

TABLE OF CONTENTS

Chapter **Page**

TABLE OF CONTENTS
(Continued)

Chapter **Page**

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

CHAPTER 1

INTRODUCTION

Waste is generated as an end product of various activities in a society and originates from household, communal and industrial sources. Wastewater treatment involves the application of scientific and engineering principles to the removal of contaminants from municipal and industrial wastewater [25]. In ancient times waste disposal was mainly in water bodies and land. The natural assimilative capacity of rivers and streams degraded these wastes and maintained their pristine condition. But with industrialization and rapid progress in technology to elevate the standard of living, this natural capacity was exhausted. Progress in technology resulted in the introduction of various substances, which were and still are harmful to both nature and man and resistant to degradation. Waste disposal and treatment, which continued without any improvement, resulted in epidemics of cholera, typhoid and many other water-borne diseases. Koch's and Pasteur's germ theory revealed strong correlation between polluted water and disease transmission [8]. The present day wastewater treatment processes and facilities are designed to operate to achieve a high standard of performance to ensure the ultimate goal of public health.

To comply with strict environmental regulations and to reduce the escalating cost of treatment process there is a need for adopting methods capable of optimizing treatment methods and resource utilization. With advancement in computers and control technologies, use of intelligent process control was introduced in several industries as a solution. Due to the complex and uncertain nature of the parameters involved in wastewater treatment the use of intelligent process control has been rather slow compared

to other fields. Research directed at achieving high standard of treatment, combining the knowledge of microbiology, wastewater treatment principles, automation and control engineering is making rapid progress, that will ensure a high quality of performance from wastewater treatment plants [24, 25].

The Upflow Anaerobic Sludge Blanket (UASB) process was developed in Holland in the late seventies. It is a widely used high rate anaerobic system for treating municipal sewage and industrial wastewater and sludge and currently more than 200 full-scale plants are being operated worldwide [2]. The UASB process incorporates several advantages of anaerobic systems such as high volumetric loading rates, low energy usage and sludge production and merits specific to it like ability to handle higher loading rate than anaerobic contact process and lesser operating problems than anaerobic filters [2]. The efficient performance of an UASB reactor, like any other system involves a thorough understanding of the process operations and the influence of important parameters. Hence the success of treatment plants heavily relies on the process knowledge and experience of operators. Introduction of intelligent control in wastewater treatment can be developed by incorporating the fundamental aspects of the underlying process and input from the plant operators. Since a large number of UASB systems are widely used around the world, incorporating intelligent process control mechanism in its operation can significantly enhance the process stability and reactor performance.

The objective of this research was to conduct an extensive study of the UASB process and identify the key elements that influence reactor performance, as the initial step in developing a simple control and diagnostic tool to control the process operation. A simple Human Machine Interface (HMI) was to be developed to accept and store operator

input in a database for future reference and decision-making ability. The application will also be capable of accessing real time data acquired by sensors and using this information to evaluate the reactor situation at any given time. The Algorithms used for evaluating data are to be based on validated models and fundamental relationships between various process parameters in anaerobic digestion as applied to the UASB process.

CHAPTER 2

BACKGROUND STUDIES

2.1 Wastewater

Man generates solid and liquid waste as an end product of his day-to-day activities. Waste generation has always been an unavoidable part of urbanization and development. Tchobanoglous and Burton (1991)[8] has defined wastewater " as a combination of the liquid- or water-carried wastes removed from residences, institutions, and commercial and industrial establishments, together with such groundwater, surfacewater and stormwater as may be present." Thus raw wastewater contains liquid waste from residence, street runoffs, mud, decaying plants and animals and other organic matter, and a host of disease-causing pathogens, and toxic substances. The organic contents in untreated wastewater, if not properly disposed will start decomposing and turn it into a breeding ground for disease vectors and a source of unsightly and odorous conditions. Such a situation is both a public nuiscence and health hazard.

Storm water and wastewater collection systems existed in the ancient civilizations and all through the 1800's and early 1900's. But the early form of treatment was disposal of untreated wastewater into large bodies of water thus polluting them. Strong evidence that polluted water was the major culprit in the transmission of many diseases lead to serious changes in treatment systems. This, together with awareness of environmental well being and sustainable development brought about a deluge of environmental laws aimed at preserving a healthy environment by cleaning up the polluted land, water and air

and treating, reusing and disposing the waste generated in the safest and the most economical way possible.

Wastewater treatment operations are basically divided into three categories – primary, secondary and tertiary [8]. Primary treatment consists of physical separation of floating and settelable impurities through screening and sedimentation. Secondary treatment employs chemical and biological methods of reducing the organic load in wastewater while tertiary treatment is a physicochemical process of removing inorganic nutrients especially phosphate and nitrate in the final effluent from secondary treatments through precipitation, filtration etc [8].

Unit operations in wastewater treatment are significantly influenced by wastewater characteristics that may be broadly classified as physical, chemical and biological. These characteristics vary with the source of wastewater and influence the selection of operation treatment options. The physical properties include color, odor, solids content, etc. Chemical properties describe the organic and inorganic contents. Organic matter can include carbohydrates, proteins, volatile organic compounds, fats, oils and grease, priority pollutants, etc while inorganic matter is seen as alkalinity, heavy metals, pH, nutrients like nitrogen, phosphate, etc. In addition to these, wastewater also contains gases like hydrogen sulfide, methane, and oxygen. Biological properties indicate presence of microorganisms like bacteria, viruses, protozoa and other plant and animal matter.

2.2 Biological Treatment

Most of the ancient civilizations can be traced to originate from the banks of rivers. These surface waters were used as a source of drinking water as well as means of waste disposal. In nature, when waste is introduced into rivers and other natural water bodies, a biocenosis, (a community of microorganisms) develops over a period of time which is capable of degrading this waste and this phenomenon is called autotreatment [21]. Thus the natural assimilative capacity of the rivers and streams degraded the waste. But waste created as a result of industrialization and urbanization exhausted this capacity. The correlation between illness and disease pathogens traces its origin to pollution of natural waters by untreated wastewater. As a result, primary treatment involving settling of solids by gravity came into existence followed by secondary treatment methods which were used to improve primary treatement. The biological treatement process used in wastewater industry is the technical version of the natural process of autotreatment [21].

Aerobic and Anaerobic process are different types of biological treatment. Aerobic process is the biological oxidation that occurs in the presence of molecular oxygen while in anaerobic process biological oxidation occurs in the absence of oxygen. The reactions can be summarised as shown below [21].

Aerobic Mechanism : -

Organic matter + microorganisms + O_2

$\rightarrow$ $5CO_2 + 2H_2O + NH_3$ + new microorganisms + energy

Ammonia is further oxidized to nitrate and nitrite .

In anaerobic process, the microorganisms obtain the oxygen required for oxidation from either the organic matter itself or from inorganic compounds like nitrates, nitrites sulfides etc.

Anaerobic Mechanism : -

Organic matter + microorganism + inorganics (nitrates, nitrites, sulfides,etc)

→ CO_2 + new microorganisms + energy
+alcohols, aldehydes and volatile acids

Then, methanogenic bacteria utilize these products to form the end products of anaerobic digestion- methane, carbon dioxide, newmicroorganisms and energy

2.3 Kinetics of Biological Growth

The biological treatment systems are mediated by bacteria and the provision of conditions favorable to their growth kinetics results in efficient treatment systems. The rate of bacterial growth in a continuous culture system is defined as [8]

$$r_g = \mu * X \qquad (2.3.1)$$

where, r_g = rate of bacterial growth, (mg/l-d)
μ = specific growth rate, (d^{-1})
X = concentration of microorganisms, (mg/l)

The effect of limited substrate on the growth of microorganisms are expressed by Monod's equation,

$$\mu = \frac{\mu_m * S}{K_s + S} \qquad (2.3.2)$$

where, μ = specific growth rate, (d^{-1})

μ_m = maximum specific growth rate, (d^{-1})

S = limiting substrate concentration surrounding the microorganism (mg/l)

K_s = half- velocity coefficient (mg/l)

The rate at which new cells are produced is related to the rate of utilisation of substrate by the relation,

$$r_g = - Y * r_{su} \qquad (2.3.3)$$

where, r_g = rate of bacterial growth, (mg/l-d)

Y =yield coefficient, (mgVSS/mg COD)

r_{su} = substrate utilisation rate, (mg/l-d)

Substituting the values of r_g from Eq (2.3.1) and μ from Eq (2.3.2) in Eq (2.3.3) we get

$$r_{su} = \frac{\mu_m * X * S}{Y(K_s + S)} \qquad (2.3.4)$$

Considering other factors like death and predation in bacterial systems, the net bacterial growth rate, r'_g and net specific growth rate, μ can be modified as

$$r'_g = - Y * r_{su} - K_d * X \qquad (2.3.5)$$

$$\mu' = \frac{\mu_m * S}{(K_s + S)} - K_d$$

where, k_d = Decay coefficient, (d^{-1})

The kinetic parameters vary with microorganisms, type of substrate, environmental conditions like temperature and pH. Tables (2.3.1) and (2.3.2) show the different values for the kinetic parameters.

Table 2.3.1 Representative values of the kinetic constants in the acid-phase and methane-phase of anaerobic digestion at 35 °C [27]

Process	k (mgCOD/mg VSS-d)	Y (mgVSS/mg COD)	K_s (mg COD/l)	μ_m (d^{-1})
Acidogenesis	13	0.15	200	2.0
Methanogenesis	13	0.03	50	0.4
Overall	2	0.18	....	0.4

Table 2.3.2 Kinetic constants for various substrates utilized in anaerobic reactors (mesophilic) [27]

Substrate	Process	k (mgCOD/ mgVSS-d)	K_s (mgCOD/l)	μ_m (d^{-1})	Y (mgVSS/ mg COD)	k_d (d^{-1})
Carbohydrates	Acido-genesis	1.33 –70.6	22.5-630	7.2-30	0.14-0.17	6.1
Long-chain fatty acids	Anaerobic oxidation	0.77– 6.67	105-3180	0.085 -0.55	0.04-0.11	0.01-0.015
Short-chain fatty acids*	Anaerobic oxidation	6.2-17.1	12-500	0.13-1.20	0.025-0.047	0.01-0.027
Acetate	Aceticlastic methano-genesis	2.6-11.6	11-421	0.08-0.7	0.01-0.054	0.004-0.037
Hydrogen/ Carbondioxide	Methano-genesis	1.92-90	$4.8 * 10^{-5}$	0.05-4.07	0.017-0.045	0.088

*Except acetate

2.4 Anaerobic Digestion

Anaerobic methods were first used in the field of sewage treatment towards the end of the last century in France by M. Mouras [1]. The other systems developed later included septic tanks by Cameron in England and imhoff tanks by Imhoff in Germany [1]. In the early days, neither the basic concept of anaerobic digestion nor the importance of good contact time between microorganisms and organic matter was recognised. Hence anaerobic processes failed miserably in stabilising waste and soon lost their popularity due to the odor problems, long initial startup times, high temperature and poor quality of effluent. The past few decades have seen the reemergence of anaerobic systems in treating wastewater mainly due to extensive research done in this field.

2.4.1 Digestion Process

Anaerobic Digestion basically consists of the breakdown of, complex organic matter into simpler components by microorganisms. The degradation is accomplished through the symbiotic relationship between several types of heterotrophic microorganisms mainly bacteria which uses the organic matter (substrates) as energy source for cellular building activities, while converting them to products which are used as food source by a different kind of microbes [22]. Though there are many stages for the degradation [1,15] they can be broadly grouped under two main reactions – Hydrolysis / Acidogenesis and Methanogenesis (Fig 2.4.1). The microbes responsible for these reactions have distinct characteristiscs and optimum conditions and the success of anaerobic treatment relies on the ability to achieve these conditions during the operation of an anaerobic reactor.

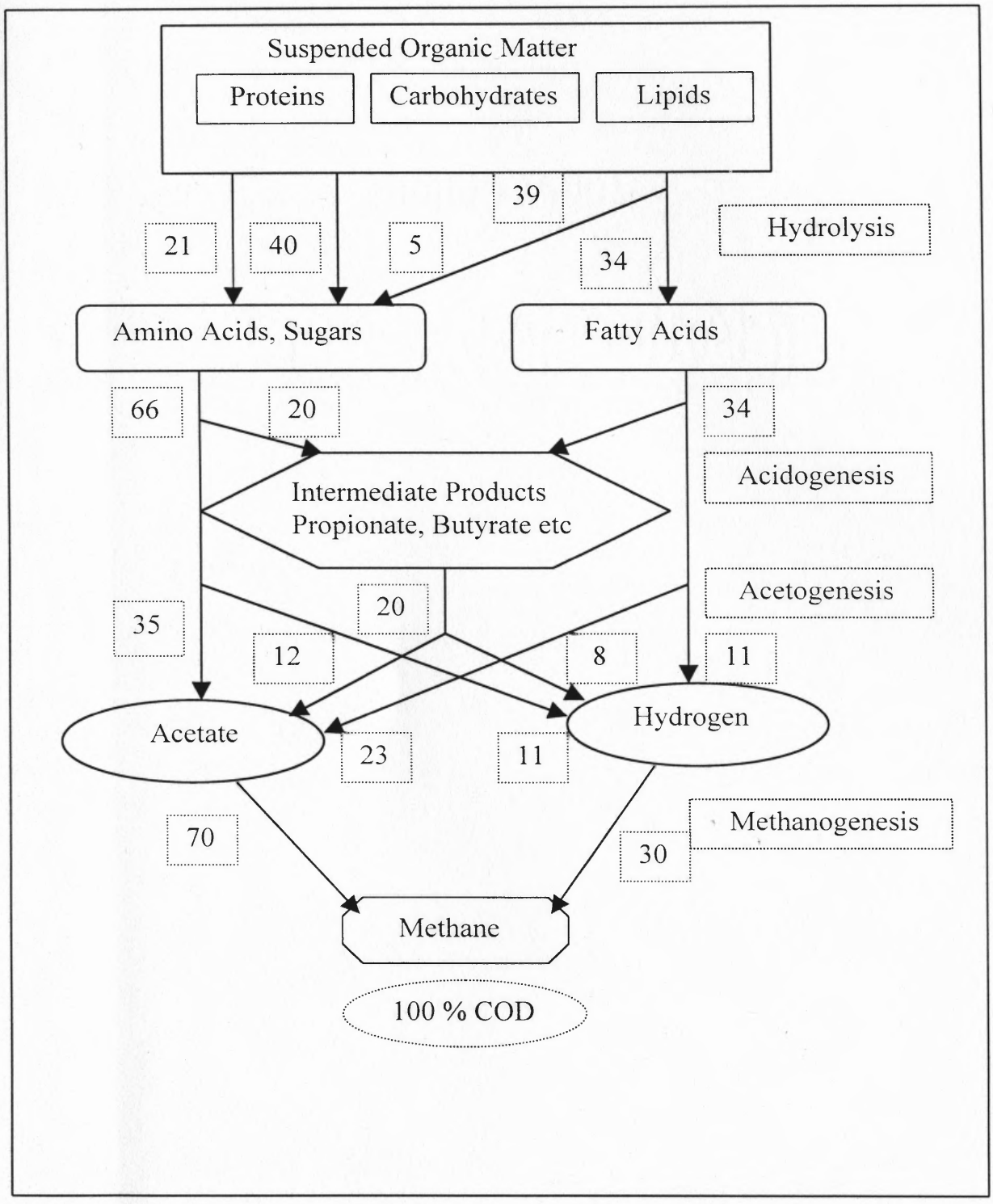

Figure 2.4.1 COD mass balance in anaerobic digestion [2] (numbers refer to percentage expressed as COD)

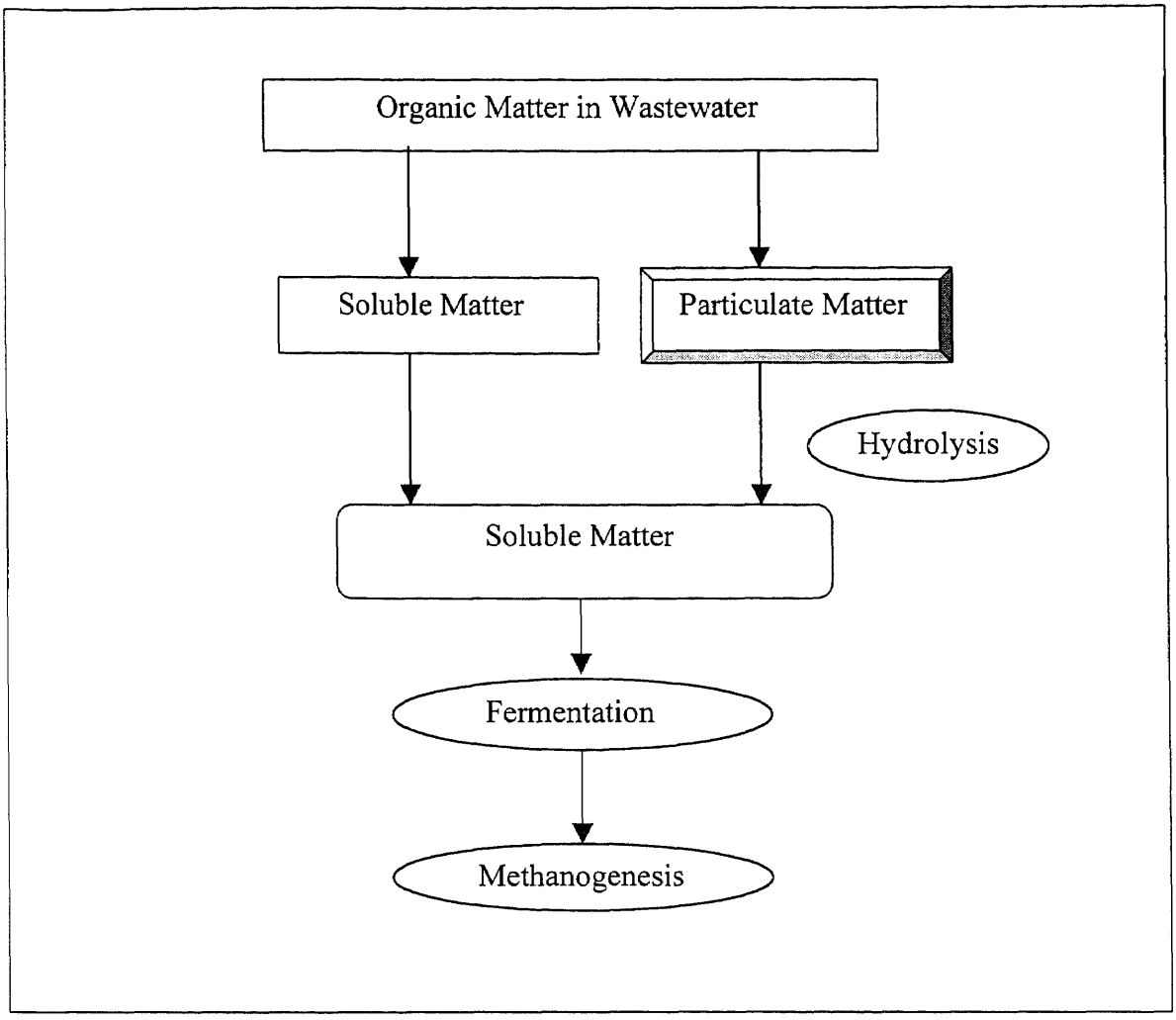

Figure 2.4.2 Hydrolysis of particulate matter

a. Hydrolysis / Fermentation

Organic matter consists of particulate and soluble matter. Soluble matter is mainly composed of smaller molecules (that are easily diffused through the cell wall of bacteria) and hence is readily available as substrate(food) to the microorganisms while particulate matter containing dead cells, complex polymers like carbohydrates, proteins, lipids and fats, have to be broken down into their simple monomeric units like mono and poly saccharides, amino acids etc, for consumption. This is achieved through hydrolysis as shown in Figures (2.4.1 and 2.4.2). The Extracellular enzymes of bacteria breaks up the complex structure of organic waste. The reactions and the various biochemical pathways taking place during the hydrolysis of particulate matter have been described in Eastman (1977)[15].

Particulate carbohydrates **Soluble carbohydrates**

complete hydrolysis

(starches, pectin, cellulose etc) ⟶ (hexose, glucose etc)

Particulate nitrogenous matter **Soluble nitrogenous matter**

complete hydrolysis

proteins ⟶ amino acids

Particulate lipids **Soluble lipids**

complete hydrolysis

lipids ⟶ long chain-fatty acids (mainly)

In the second part of hydrolysis, the fermentation of these hyrolysis products leads to the formation of volatile fatty acids which is a mixture of acetic, propionic, isobutyric, n-butyric, isovaleric, n-valeric, caproic acids, etc and minor products like lactic and formic acids and $C_2 - C_4$ alcohols, carbondioxide, and hydrogen[22,23]. These intermediate products are converted to acetate, carbondioxide and hydrogen. Propionic and butyric acids are long chain fatty acids and they are first broken down to short chain acetic acid.

The facultative bacteria responsible for hydrolysis and acid fermentation are collectively called " Acid formers". It has been found that solubilization and acid fermentation can take place even at low levels of pH and temperature [14]. Acid formers include species belonging to the family of *Streptococcaceae, Enterobacteriaceae and genera of Bacteriods, Clostridium, Butyrivibrio, Eubacterium and Lactobacillus* [22]. Acid formers are saprophytes and fast growers with a yield coefficient of 0.15 mg VSS/ mg COD [1]. So roughly, 5 / 6 th of a combined culture growing on a complex organic substrate will be of acid-formers [1]. The production of volatile fatty acids (VFA's) depends on many parameters like hydraulic retention time (HRT), operating temperature, and wastewater characteristics.

Hydrolysis is an important stage as it improves biological nutrient removal and increases concentration of soluble organic matter (change in COD of wastewater comes only with the hydrolysis of particulate matter to soluble matter which can be easily degraded by microbes [14]. Studies conducted in the acid-phase (hydrolysis /fermentation) of anaerobic digestion have shown that not all compounds are hydrolysed and fermented equally - carbohydrates and nitrogenous compounds are mostly fermented in the acid-phase itself while lipids fermented along with volatile fatty acids during the

methanogenesis [13,14]. The rate of hydrolysis depends on many factors like surface- to-volume ratio of particles i.e. that rate of hydrolysis of larger particles will be less compared to smaller particles due to their low surface –to-volume ratio, pH, temperature, type of particulate substrate, concentration of degradable particulate matter remaining etc [13,14,15]. Eastman and Ferguson (1981)[14] also points out that the presence of compounds like lignin and wax etc around particulate matter can delay the hydrolysis by preventing actual contact with microbial enzymes. So many of the researchers have adopted a first-order function for rate of hydrolysis, which caters for the different hydrolysis rate of compounds when considering a complex substrate [13,14]. The rate of hydrolysis is different from the rate of fermentation (as mentioned in Eastman (1977)[15]) and so there may not be any accumulation of hydrolysis products.

b. Methanogenesis

Methanogenesis is the final stage in the decomposition process. In this stage methane is formed from two products, acetate and hydrogen. One group of microorganism converts acetate to methane and another group converts hydrogen (which is another intermediate product found only in negligble quantity in the product gas, usually less than 3%) to methane as shown by the following reactions [1],

Acetotrophic Methanogenesis - $CH_3COOH = CH_4 + CO_2$

Hydrogenotrophic Methanogenesis - $4H_2 + CO_2 = CH_4 + 2H_2O$

Though there are two pathways for the formation of methane, it can be seen from the Figure 2.4.1 that only 30 % of methane is formed from hydrogenotrophic methanogenesis while 70 % is formed from acetotrophic methanogenesis.

The microorganisms reponsible for methanogenesis are collectively called "Methanogens" and they include species like *M. Formicicum, Methanobacterium Omelianskii and Methanobacillus (Rod Shaped), Methanothrix, Methanosarcina Barkerii and Methanococous Vannielii (Spherical Shaped), etc* [9,10,11]. Unlike acid formers, methanogens are slow growers (hence this step is often considered the rate-limiting step in anaerobic digestion) having minimum generation time ranging from 1.68 to 4 days and a low yield of 0.03 mg VSS / mg COD [1,2,3]. So approximately, one-sixth of a culture formed from a complex organic substrate will be composed of methanogens [1]. The methanogens are extremely pH sensitive and thrive well in the range of 6.5 to 8.0 (the pH range in which anaerobic reactors are operated), having optimum growth at 7.2 to 7.4 [22]. Methanogens are obligate anaerobes and use carbondioxide as hydrogen acceptor and acetate, alcohols, Butyrate etc, as hydrogen donor while ammonia is the nitrogen source [22]. It has been seen that, depending on the amount of substrate available (acetate) one particular bacterial species will dominate the others. As an example , *Methanothrix* has a Saturation constant, K_s value of 30 mg/l and a specific growth rate, μ_m value equal to 0.1/day, while *Methanosarcina* has a K_s value of 200 mg/l and a specific growth rate, μ_m value equal to 0.3/day [1] . So, at low acetate concentration (below 55 mg/l), *Methanothrix* which has a higher specific growth rate than *Methanosarcina* and becomes the dominating species while the opposite is true at higher acetate concentrations.

2.5 Environmental Factors Influencing Anaerobic Digestion

Microorganisms which are responsible for degradation have optimum conditions for growth and survival, and change in these conditions can adversely effect the digestion process. Anaerobic digestion is influenced by many environmental parameters and some of the most important factors are discussed in the following sections :

2.5.1 Temperature

Temperature is perhaps one of the most important environmental parameter which exerts control over the growth and survival of microrganisms. It affects the microbes in two different ways ; an increase in temperature increases the rate at which chemical and other biological reactions occur in a cell leading to increased growth rates while increase in temperature above a certain value (which is specific to microorganisms) can lead to alteration in the structure of proteins, nucleic acids and other cellular components thus inactivating the cell [20]. Every microorganism has an optimum temperature for growth and it varies with the organisms.

In the Anaerobic digestion, methangens are highly sensitive to temperature variations unlike acid-formers and Zickefoose and Hayes (1976)[17] reports that the organisms function best under mesophillic conditions ($29^0C - 37\ ^0C$) and in some cases in the thermophillic range ($49^0C - 57\ ^0C$). Digestion process ceases at about 10^0C [16]. The decrease in digestion rate when functioning below the optimum range can be given according arrhenius expression [8],

$$r_t = r_{30} * (1.11)^{t-30}$$

where, t = temperature (^{0}C)

r_t= digestion rate at temperature t ^{0}C

r_{30} = digestion rate at temperature 30 ^{0}C

2.5.2 pH

pH is an important indicator of reactor stability. The optimum pH for anaerobic condtions is generally in the near neutral range of 6.5 – 7.5. Similar to temperature each organisms has an optimum pH value. Acid-formers are more tolerant to low pH (above 5.0) than methanogens which are inhibited at a pH below 6.2 [18]. Hence the methanogenesis proceed at lower rate at a lower pH, triggering a chain of events.

Inhibition of methanogens at lower pH prevents the consumption of volatile fatty acids produced by the acid-formers resulting in a further drop in the pH due acid accumulation. So even though pH is an indicator of reactor stability the reactor maybe well on its way to process failure by the time the drop in pH is noticed. But it has been noticed that anaerobic reactors can still function at lower pH after being subjected to a period of acclimitization [14].

The pH can also influence the toxicity of compounds, i.e the changes in pH can alter concentration or form of toxic substance. As an example, in wastewater, sulfides are found (mainly as hydrogen sulfide at low pH, as bisulfide ion and as sulfide ion at high pH) as the harmless metal sulfide precipitates and soluble sulfides (which above a concentration of 200 mg/l is toxic to the microbes [18]). At a higher pH, sulfide compounds can precipitate out as metal sulfides or release hydrogen sulfide as gas [15]. The pH in the reactor is maintained by many weak acid-base systems like ammonia,

phosphate, sulfate, carbonate, etc of which the carbonate system is important for maintaining pH near neutral conditions [1]. The pH can be controlled by adding chemical like slaked lime, hydrated lime, anhydrous and aqueous ammonia, sodium hydroxide, etc [18].

2.5.3 Alkalinity

Jenkins and Snoeyink (1980)[19] defines Alkalinity as " a measure of the capacity of a water to neutralize strong acid ". The various bases that contribute to this ability in natural waters are mainly bicarbonates, carbonates, and hydroxyls while silicates, ammonia, phosphates etc present in lesser concentrations have smaller influence [19] . This "ability " is important in wastewater treatment as alkalinity acts as the buffering agent against pH drops and is crucial for maintaining neutral pH conditions in the reactor, which is essential for anaerobic digestion.

Several acid-base systems are present in anaerobic treatment process like carbonate, ammonia, phosphate, sulfide and acetic acid. But since the digestion occurs best in the narrow pH range of approximately 6.5 to 7.5 and since in natural systems carbonate system is found to be present at higher concentrations, it therefore exerts a strong influence in maintaining the pH [1]. The digestion process in the reactor produces ammonium bicarbonate and calcium and magnesium bicarbonates are the other buffers found in a reactor [16].

The amount of alkalinity present in the reactor must be sufficient to neutralize the volatile fatty acids produced by the acid-formers and must also be present in excess amounts to deal with sudden pH fluctuations. The ratio of volatile fatty acids to the alkalinity is an important indicator of reactor health. In a healthy reactor, the ratio will be

less than 0.25 [17]. A value of over 0.3 indicates that rate of formation of acid is more than its consumption and hence the onset of process failure.

2.5.4 Toxicity

Toxic materials find their way into wastewater treatment facilities mainly from accidental spills and from industries like metal plating, manufacturing, chemical, petroleum, tanneries, insecticide and pesticide, etc. Heavy metals like cadmium, cobalt, copper, and compounds of phenol, cyanide, sulfide, etc are contained in the wastewater from these sources. Presence of toxic substances are very less in typical sewage. These substances are harmful to the microbes in treatment plants.

There are some other elements that are necessary for microbial growth in small quantities but can prove to be toxic at higher concentrations. e.g. cations like calcium, sodium, magnesium, etc which are growth factors can be inhibitory at higher concentrations or by a change in a parameter like the pH (as explained earlier with sulfide). There are some compounds that by their mere presence can increase the toxicity of other compounds or neutralize them. These compounds are called synergistic and antagonistic compounds respectively and they play an influential role in toxicity in reactors. The other substances which can be toxic microbes are ammonia, and dissolved oxygen. Dissolved oxygen has been considered to be toxic to both anaerobic microorganisms (acetogens and methanogens), especially to methanogens as they are obligate anaerobes. But Lettinga et al. (1997)[34] mention a study that found dissolved oxygen not to be so detrimental to methanogens. Inhibition by substrates is a phenomenon that occurs when the substrate concentration exceeds a certain value,

e.g. volatile fatty acids can be toxic to methanogens. The inhibition concentration varies with organism [1]. Effluent recycling has been found to be an appropriate solution for this problem in complex industrial wastewater [31,32].

Table 2.5.1 Concentration of various substances inhibiting anaerobic reactions [16]

Substance	Concentration mg/l	
	Moderately inhibitory	Severely inhibitory
Calcium	2500-4500	8000
Magnesium	1000-1500	3000
Potassium	2500-4500	12000
Sodium	3500-4500	8000
Sulfide	50-100	> 200
Ammonia	....	> 3000
Copper (soluble metal)	....	0.5
Zinc (soluble metal)	....	1.0
Chromium (+6) (soluble metal)	....	3.0
Nickel (soluble metal)	....	2.0

2.5.5 Nutrients

Microbes take up chemicals from their outside environment or/ and synthesize some inside their cells to perform metabolic reactions. This requires elements other than oxygen, carbon, hydrogen and nitrogen which form the backbone of the macromolecules inside the cell [20]. The essential elements include potassium, calcium, magnesium, iron, sulfur, zinc, etc and other elements specific to certain microorganisms are called growth factors. Macronutrients are needed in large amounts compared to micronutrients (trace elements) which are required only in lesser amounts. Potassium, sulfur, phosphorous, iron, etc are examples of macronutrients while chromium, cobalt, nickel, selenium, etc belong to the micronutrient category [20].

Nutritional requirements vary with microorganisms. Provision of sufficient nutrients is an essential measure to ensure proper growth and maintenance of microbes used in wastewater treatment plants. The recommended ratio for COD/N and COD/P are not be less than 70 and 350 while concentrations of trace elements like iron, nickel and cobalt at 5μm, 0.25μm and 0.10μm respectively have found to improve granulation in sludge blanket reactors [3].

2.6 Process Parameters Influencing Digestion

2.6.1 Hydraulic Retention Time (HRT)

Hydraulic Retention time is the duration for which the influent is maintained in the reactor. The mean hydraulic retention time, θ is defined as the volume of the reactor divided by the flow into the reactor,

$$\theta = \frac{V_r}{Q}$$

where, V_r = Volume of reactor (cu.m)

Q = Flow rate into the reactor (cu.m/d)

θ = Hydraulic retention time (d)

Studies on the influence of HRT and temperature on the digestion process by Cha and Noike (1997)[28] has revealed that there was a significant reduction in efficiency in the degradation of substrates in the acidogenic phase for a sudden drop to a lower temperature at short HRT than at higher HRT. They also found that the reactor regained its stability slowly at short HRT and lower temperature. The study also found that HRT changes coupled with temperature affected volatile fatty acid producing bacteria.

2.6.2 Solids Retention Time (SRT)

Solids retention time is the time period for which biological solids are retained in the reactor. It is has been defined in Tchbanoglous and Burton (1991)[8] as "mass of organisms in the reactor divided by the mass of organisms removed from the system each day". The solids retention time is denoted as θ_c and it varies with the reactor configuration. SRT is depended on the microrganism concerned, as the time for which solids have to be retained in the reactor depends on generation time of the microbes [8,18]. An SRT less than generation time results in washout of biomass. This value of SRT is called minimum SRT denoted as θ^M_c .Waste stabilization ceases below θ^M_c. The

expression for calculating minimum SRT is given in Tchbanoglous and Burton (1991)[8] as

$$\frac{1}{\theta^{M}_{c}} = \frac{Y(k * S_o)}{K_s + S} - K_d$$

where, θ^{M}_{c} = minimum solids retention time (d)

S_o, S = influent and effluent substrate concentration respectively (mg/l)

Design values for SRT are usually 2 to 20 times more then minimum SRT. The θ^{M}_{c} values for an anaerobic reactor is about 10 days (generation time for methanogens which are slow growers is 4-10 days) [18].

In conventional anaerobic systems HRT is equal to SRT. Lawrence and McCarty (1969)[29] has suggested that the process efficiency could be improved by maintaining long SRT so that microorganisms get sufficient time to grow and stabilize. This results in less wash out of microorganisms and increases the efficiency of the process. A whole range new anaerobic methods were developed seperating SRT from HRT. SRT can be separated from HRT by recycling solids from a clarifier or internal recycling by way of intermittent mixing, solids settling, and wastage of supernatant [18]. Longer SRT in anaerobic systems can achieve greater solids stabilization and biogas formation and lesser net biomass production [18]. Heated digesters have the advantage of operating at higher temperatures and shorter SRT that can achieve the same degree of waste stabilization at long SRT [8].

2.6.3 Mixing in Reactors

Mixing in reactors between organic matter and microorganisms is essential for contact between the two entities for digestion to take place. Mixing is achieved by mechanical agitation in some reactors while recycling, upward gas movement (in UASB reactors) etc accomplishes this. Inappropriate mixing results in insufficient contact between substrate and microbes and also creates channeling in sludge bed and blanket (in UASB) leading to incomplete digestion and dead zones respectively in the reactor [1].

2.7 Advantages and Disadvantages of Anaerobic Process

The main advantages of anaerobic process :

- High organic loading rates

  Anaerobic processes are capable of efficiently stabilising wastewater containing high organic content like 16 kg COD/ cu.m-d like industrial wastes [26,8]

- Minimal sludge disposal

  The amount of sludge needed to be disposed after waste stabilization is less compared to aerobic process mainly due to the slow growth rate of anaerobic bacteria and the stabilized sludge can be easily dewatered [26].

- Higher degree of waste stabilization

- Useful end Products

  Almost the entire organic matter is converted to methane which can be used as energy source.

- Preservation of active anaerobic sludge for many months unfed [26]

Some of the disadvantages of anaerobic process are :

- Longer start-up periods

  The duration of start-up of anaerobic reactors is long , often taking several weeks due to the slow growth rate of anaerobic bacteria [26]

- Effluent needs post treatment

  Anaerobic treatment is still a method of pre-treatment and the effluent needs adequate post treatment usually to remove the nutrients like nitrogen and phosphorous before being discharged

- Sensitive process

  Anaerobic digestion is vulnerable to the presence of certain toxic substances in wastewaters like cyanide, carbontetrachloride etc [26]

2.8 Types of Anaerobic Systems

Anaerobic digestion systems can be basically classified as standard and high rate reactor systems [8,18]. Standard rate reactor systems are unheated and unmixed with a detention time varying from 30 –60 days [8]. High-rate systems are on the contrary heated and completely mixed with a detention time of 15 days or less [8].

High-rate systems also contain single and two-stage process where the two-stage system combines high-rate and standard rate. The first stage consists of a completely mixed and heated system in which digestion occurs and in the second stage the digested solids are separated from the liquid portion in a clarifier [8]. There are several reactor configurations for anaerobic digestion. Anaerobic filters and expanded bed are examples

of anaerobic attached- growth systems while anaerobic contact process and upflow anaerobic sludge blanket etc are examples of suspended –growth systems.

2.8.1 Completely Stirred Tank Reactor (CSTR)

In a completely stirred tank reactor (CSTR) the contents of the reactor are thoroughly mixed. The process is efficiently capable of stabilizing waste from meat industry and high –strength soluble waste [8]. Tchobanoglous and Burton (1991)[8] has shown, for typical values of influent COD of 1500 – 5000mg/l, this process was able to achieve 75 – 90% COD removal at HRT of 2-10 hours at organic loading rate of 0.03 –0.15 lb. COD / cu. ft.-d. The digestion occurs in a reactor where the organic matter in wastewater comes in contact with the microorganisms. After the required detention time the digested solids flow into a clarifier where the stabilized solids are separated from the liquid portion. The clear effluent is drawn off and the settled solids are drawn from the bottom and directed back into the reactor to act as seed material. The mixing is achieved by recirculation of digested solids from the clarifier.

In a completely mixed system, as explained earlier separation of SRT and HRT leads to good waste stabilization. A constant biomass concentration is maintained by wasting a calculated amount of biomass either from reactor or recycle. The SRT in a system without recycle will be equal to its HRT. For a system with recycle, the expression for SRT, θ_c is given by [8],

$$\theta_c = \frac{V_r X}{Q_w X + Q_e X_e}$$

where,

θ_c = Solids retention time (d)

V_r = Volume of the reactor (cu.m)

X = Concentration of microorganisms in the reactor (mg/l)

X_e = concentration of microorganism in the effluent (mg/l)

Q_w = Flowrate of liquid containing microbial mass wasted from reactor (cu.m/d)

Q_e = Flowrate of effluent (cu.m/d)

If the wastage is from the recycle line the expression is modified as

$$\theta_c = \frac{V_r X}{Q'_w X_r + Q_e X_e}$$

where, X_r = concentration of microorganism in recycle (mg/l)

Q'_w = flow rate of wastage (cu.m/d)

2.8.2 Upflow Anaerobic Sludge Blanket (UASB) Reactor

The Upflow Anaerobic Sludge Blanket (UASB) is a popular anaerobic treatment of concentrated municipal and industrial waste water. The concept was developed by Prof. Lettinga of Holland in the 70s for treating low strength waste and short hydraulic retention times. In UASB process the separation of SRT and HRT resulted in the formation of granules of sludge and biomass which improve the degradation process. Van Velsen et al. (1980)[26] describes UASB as " a modified version of the contact process is based on the upward movement of the liquid waste through a dense blanket".

The UASB reactor consists of four zones [1,2,3] (Figure 2.8.1):

- **Sludge bed**

  This is the lowest zone in the reactor occupying about one third of the reactor volume and is a dense formation of biomass and sludge granules. The sludge bed is situated at the influent entry and had the highest concentration of solids.

- **Sludge blanket**

  This zone is located above the sludge bed and consists of sludge particle and biomass held together in supsension by gas produced as a result of degradation in the sludge bed. The concentration of solids in the sludge blanket reduces with the height of the blanket in the reactor. The sludge blanket characteristics has to be understood well (due to its importance in degrading organic matter) to obtain optimum reactor dimensions to encourage blanket formation [4].

- **Phase separator**

  This is a gas- liquid separating device located in the upper level of the reactor. The biogas formed as a result of the Anaerobic reaction, is separated from the liquid in this region and is collected separately.

- **Settling zone**

  The settling zone is situated next to the phase seperator where the solids rising to the surface settle out from the effluent into the sludge bed.

The wastewater is introduced from the bottom of the reactor and it flows upwards passing through various zones. The organic matter is decomposed by the microbial population present in the sludge bed and the sludge blanket. Some of the sludge particles migrate up along with the biogas bubbles produced. The increase in area of the reactor

near the phase separator reduce the upward velocity and particles settle on the inclined surface of the reactor. They grow heavier and finally settle to the bottom. Meanwhile the clear effluent goes out through the outlet and the biogas is emitted through the gas- liquid separating device.

As discussed earlier, temperature, pH, alkalinity etc influence the efficiency of the process. Different studies conducted on UASB process on the dependence of temperature, performance at various organic loading rates and formation of granular sludge, etc emphasize the importance of these parameters[5,6,7]. UASB process is mainly used to treat high strength biologically degradable waste water from potato, fruits and other food processing industries, paper and pulp industry, brewery and distillary industry. Hybrids of the process have been developed combining the advantages of different methods and the expanded granular sludge bed (EGSB) and two stage anaerobic digestor are examples.

Full-scale UASB reactors are constructed mainly of concrete and steel. The dimensions are governed by the type of waste, hydraulic/organic loading, hydraulic retention time, liquid velocity etc. The upward liquid velocity is related to the cross-sectional area of the reactor by,

$$V_i = \frac{Q}{A}$$

where, V_i = upward liquid velocity (m/h)

A = cross-sectional area of reactor (sq.m)

Q = flow (cu.m/d)

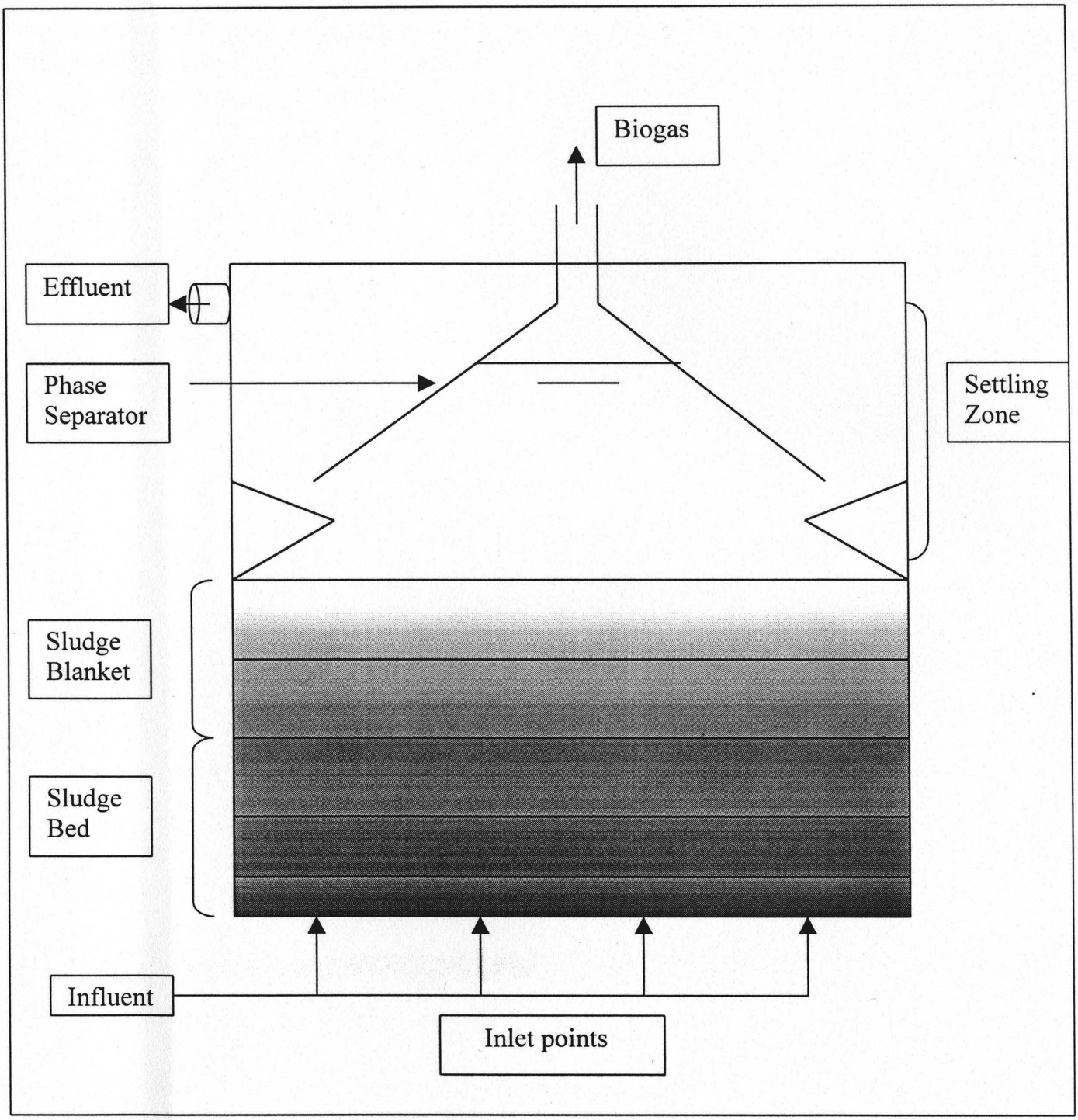

Figure 2.8.1 A Schematic of a UASB reactor

A reactor height of 4-6m is normally used [1,3]. Dimensions are chosen to provide adequate settling. The reactor shape can be either circular or rectangular and depending on the convenience of construction. Circular shape is used for small reactors while square or rectangular shape is used for large reactors and when more than one unit is being constructed.

The gas-solid separating devices are designed for effective separation of biogas from the liquid phase while allowing the solids to settle back in to the reactor [3]. The inlet systems are designed to enable uniform distribution of influent into the reactor and typical values are one distribution point per 7-10 sq.m horizontal area for organic loading greater than 6 kg COD/ cu.m/d and one distribution point per 1-2 sq. m. horizontal area for diluted waste [3]. Haandel and Lettinga (1994)[1] suggest after the initial start-up, inlet points at 2-4 sq.m at temperature over 20 °C and 1-2 sq.m at temperature lower than 20 °C. The concept of the design is that at lower temperatures, gas production is less and so insufficient mixing between substrate and biomass has to be compensated by higher density of influent points.

The granulation process is found to develop in four steps [3]

- Transport of cell to inert materials or other cells (together called substratum)
- Reversible adsorption to substratum,
- Irreversible adhesion to substratum by polymers or appendages and finally
- Cell multiplication and development of granules.

There are several factors affecting granulation [3]. The type of sludge seed influences granulation. Sediments from septic tanks, raw sewage, cattle manure and digested sewage sludge are the different sources of sludge seed but digested seed is commonly used.

Granular sludge if used as seed material reduces the start-up time as it contains highly active biomass. But some problems can occur if the starter seed material was grown in a wastewater composition different from the wastewater to be treated [3].

Temperature is another important factor and granulation occurs well both in mesophilic (30 °C – 35 °C) and thermophilic (55 °C – 60 °C) conditions but slower at lower temperatures (< 20 °C). At lower temperature the growth of biomass is very slow and the start-up is prolonged. The specific activity of sludge at 35 °C is more than twice the activity at 20 °C and six times more than the activity at 10 °C [3].

Wastewater composition can accelerate the granule formation or inhibit it. Wastewater influent composed of soluble carbohydrates, volatile acid mixture and from sugar beet, potato processing, yeast industry etc aids granulation. Proteinous waste too encourages granulation but at high loading rates creates problems like foaming and can upon degradation release ammonia, which at concentrations above 3000mg/l inhibit microbial activity [3,26]. The presence of fine particulate matter, which have poor flocculation have been found detrimental to granular sludge formation [26]. Bacteria attach itself to the fine particles, which do not settle down and are subsequently washed out. In a study of sugar-beet campaign wastewater by Velsen et al. (1980)[26] moderate treatment efficiency (87%, compared to 95% in other reactors) was observed in the reactor due to the presence of finely dispersed and poorly biodegradable matter, which accounted for 10 – 20% of the COD. The same study mentioned above showed a drop in the COD removal due to nutrient deficiency (phosphate), which was regained immediately upon nutrient supply. Besides phosphorous, adequate supplies of nutrients like nitrogen, sulfur etc and trace elements like Fe, MO, Ni, CO, etc enhance granulation

[3,26]. Presence of heavy metals, sulfides, cyanide, oxygen, etc inhibit microbial growth and hence granulation.

Table 2.8.1 Concentration of various elements enhancing granulation [3]

Element	Concentration
Fe	5 μM
Ni	0.25 μM
CO	0.10 μM
Ca^{2+}	150 mg/l
Na^{+}	350 mg/l
NH_4^{+}	> 1000 mg/l
S^{-2}	0.1mM

Sludge granules and organic matter in wastewater has to be adequately mixed for proper contact for degradation to occur. Mechanical mixing may be used initially with a value of 10- 30-rpm for 1min per 10 min. Once a good sludge blanket is formed, it can usually withstand high mixing forces. The optimum pH for sludge granulation is 7.0 and pH either below 6.5 or above 7.5 is harmful to methanogenic bacteria. Chemicals like sodium Bicarbonate, ammonia, and lime can be added to keep the pH stable. Adequate organic loading above 0.6 Kg COD / Kg VSS/ d is needed for granulation [3]. But both organic underloading and overloading adversely affect the sludge formation process. If inadequate loading has been applied, voluminous sludge develops which does not have good settlability and this results in sludge washout. It has also been found that addition of small amounts of crushed granular sludge can enhance the granulation process.

The shape and the composition of the granules vary with wastewater and operating conditions. Typically they are spherical with diameter ranging from 0.14mm to 5mm. Buoyant density, volume and settling velocity are characteristics of granules, which determine their ability to settle down in the reactor or be washed out. The typical reported settling velocity is between 18 and 50 m /h while values for buoyant densities are 1.03 to 1.08 g /ml [3,5]. The granules contain inorganic materials like calcium, potassium, iron, sulfur, aluminum, silicon as ash contents and compounds like silicates and sulfides etc [5,9]. The percentage of ash content varied with change in substrate and temperature. The extracellular polymers (ECP) produced by bacteria, containing proteins, polysaccharides and lipids also contribute to the formation of granules and to the adsorption of bacterial cells on to surfaces.

The performance of different bacterial groups in the digestion process can be measured in terms of specific activity (SA), which is proportional to the available biomass of the bacterial group for the given substrate. Granular sludges have high methanogenic activity having a typical value of 0.5-2 g COD-CH_4 / g/VSS/day. SA depends on the growth substrate of the granules and is inhibited by high concentration of fatty acids. Properties of granular sludge can be improved or new ones can be developed to increase the efficiency of the degradation process, e.g. addition of supplementary carbon source can increase the dechlorination efficiency of pentachlorophenol. The granules may contain different microbial population, which change with wastewater composition and temperature. The typical microbial species include *Methanosarcina spp., Methanosaeta spp., syntrophomonas spp., Desulfovibrio spp., etc.* Among these species *Methanosarcina and Methanosaeta* are significant aceticlastic species in the

granules. The precise nutritional requirements for the microbes for granulation are not known, adequate amounts of nitrogen (COD / N below 70), phosphorus (COD/N below 350), calcium (80-100 mg/l) have been observed to influence granulation [5,9]. *Methanosaeta* grow only on acetate while *Methanosarcina* species utilize other methanogenic substrates like methanol, H_2 / CO_2, etc. *Methanosarcina* species can be dominant when UASB reactor is operated under both mesophilic and thermophilic temperatures using various substrates.

The surfaces of the granules are rough and uneven and contain cavities, which function as channels for gas and substrates transportation [3]. An internal organization is observed among the various bacterial groups in the granules and these habitat patterns changes depending on the wastewater characteristics. e.g. in the presence of acetate, aceticlastic groups are found to dominate the outer surface of granules.

The start-up of the UASB reactor depends on a lot of parameters- availability and type of seed material, hydraulic and organic loading, operating temperature, etc [3]. If granular sludge is used as the seed material the start-up period might be only a month while digested sludge seed can take up to 2 months to start [3]. If the substrate to degrade is different from the growth substrate of the granules, inhibitions and toxic effects can occur resulting in the failure of granulation [3]. Disintegration of granules can also occur if sludge grown under mesophilic conditions is used in a thermophilic reactor [7]. Sludge washout occurs in a reactor during early stages of start-up due to bed erosion or sludge bed expansion [3]. The washout in the former case is due to the selection process, which eliminates fine sludge particles (which do not form settalable sludge) resulting in well

settled sludge while the latter situation will retard granulation process if not minimized [3].

The hydraulic retention time (HRT) must be long, initially to allow for biomass retention and granulation and prevent biomass washout. Once the sludge blanket and bed has developed the HRT can be slowly reduced to the design value as shown in Davlyatshina et al. (1996)[6]. Velsen et al. (1980)[26] suggests applying an organic load in the range of 0.1 -0.2 kg COD/kg TS /d. Lin and Yang (1991)[3] recommends the initial loading rate to be 0.05 –0.1 kg COD/kg VSS/d and not exceeding 0.2 –0.4 kg COD/kg VSS/d for completely biodegradable waste like volatile fatty acids. The loading rate can be gradually increased once the unsettalable sludge particles are selectively eliminated resulting in the formation of a good sludge bed with high settling ability and active biomass.

The UASB process can be used to treat a wide variety of wastewater. The source can include industries processing sugar, fruit and vegetables, breweries, distilleries, starch, yeast, meat, dairyproducts, paper mills, etc [1,3]. The ability of the process to degrade waste and produce effluent of high quality required by regulations heavily depends on the formation and retention of a good sludge bed within the reactor. A good start-up phase considering all the significant factors discussed in earlier paragraphs. But in order to sustain the good quality sludge in the reactor favorable physical and chemical conditions have to be maintained in the reactor. The sludge retention is dependent on operational characters like hydraulic and organic loading rates for a given waste, reactor and sludge [26]. Therefore the success of treatment heavily relies on the ability of the

plant operator to create suitable environment in the reactor by adjusting the operational parameters.

High organic and hydraulic loading (5-18 Kg/ cu. m. /d) can be applied for soluble waste while for partially soluble waste, moderate hydraulic loading (0.5 – 5 Kg/ cu.m/d) is used [3]. Studies have been conducted to test the performance of the UASB reactor under various organic loading rates [6]. The experiment was done using wastewater from milk treating industry and the organic loading rate (OLR) was increased from 3.4 g to 44.9 g COD/ l.-day. It was found that other than temporary disturbance occurring during the time of change in loading, the removal efficiency did not suffer any significant changes (it changed to 97% from the initial 98 %). So there should only be a gradual increase in the initial organic loading rate to the design value else it would result in biomass washout and poor performance of the reactor. In the absence of adequate mixing of the incoming waste and reactor contents, either mechanically or by gas evolution, the wastewater can travel through cracks and canals in the sludge bed creating dead zones [1,3]. High hydraulic loading rates can break up sludge particles although a well-settled sludge blanket is capable of withstanding high mixing forces [3]. High organic loading rates increases gas production resulting in expulsion of gas entrapped in the sludge bed and leading to its thickening. Increase in loading rates can also result in increased concentrations of volatile fatty acids and other compounds like ammonia (in the case of overloading of proteinous waste) which can lead to inhibition of microorganisms especially methanogens.

A study conducted by Campos and Anderson (1992)[30] on the effect of varying upflow velocities in a UASB reactor found that at high upflow velocities resulted in

better selection of sludge and good mixing characteristics in the reactor. Effluent recycle is one operational strategy for dealing with toxic conditions in the reactor and while treating complex wastewater containing high concentrations of proteins, lipids and refractory organics [12,31,32]. During a study conducted by Paik and Shin (1990)[12], the bottom of the reactor became overloaded with proteins and lipids resulting in sludge flotation, formation of scum layer and loss of biomass. In this situation, recycling lessened the overloading and helped in retention of sludge.

The optimum pH for anaerobic digestion in the reactors is in the neutral range of 7.0. The typical operating temperatures are in the mesophilic range of 30 °- 35° C, but UASB reactors also function at thermophilic range of 55° C and as low as 8° -20° C [3,7]. Some industries discharge wastewater with temperatures exceeding 90° C due to their heat processing operations. In this case, to save on energy and equipment to cool the wastewater Tseng et al. (1995)[7] studied the performance of thermophilic UASB reactor at 65° C using wastewater-containing sucrose. It was found that though there was an increase in the acetate-utilizing methanogenic activity, with the increase in temperature from 55°C to 65° C, the overall performance of the reactor was less satisfactory at 65° C compared to performance at 55°C. The failure could be as a result of the disintegration of the granular sludge.

The UASB process can be modified to treat wastewater at temperatures lower than 18°C. Expanded granular sludge bed (EGSB) reactor and the 2-step UASB reactor are the modified forms of it. The EGSB reactor operates at a higher upward velocity of 6-12 m/h [1], which keeps the granular bed in suspension for a greater height than in the UASB. This also promotes excellent mixing between incoming waste and sludge

particles resulting in better removal of organic matter. EGSB is suited for operating at low temperatures and low strength wastewater though inadequate for particulate organic matter [1]. The 2-stage anaerobic digestive system is suited for treating sewage with large particulate organic fraction [1]. It contains two-reactor systems- the first stage is a hydrolytic reactor where some portion of the particulate organic matter is converted into soluble compounds. These compounds are then digested in the second reactor.

The main advantages of UASB reactor are that it enables a high COD removal efficiency at shorter retention time, low energy requirements, simple reactor construction and absence of support media. The disadvantages are that it is sensitive to hydraulic and organic shock loads and the granulation process is influenced by wastewater composition and presence of elements like Ca, ammonia that could inhibit it.

CHAPTER 3

MATHEMATICAL MODELS

3.1 Estimation of Alkalinity

Alkalinity is defined as the ability of water to neutralize acids [19,33]. In natural waters, alkalinity is contributed mainly by bicarbonates, carbonates, hydroxides, etc [19]. In wastewater treatment, this alkalinity acts as the buffering agent against pH fluctuations. This is crucial for maintaining neutral pH conditions in the reactor, which is absolutely essential for anaerobic digestion. Carbonate, ammonia, phosphate are acid-base systems present in wastewater treatment plants [1]. Within the pH range of 6.5 –7.5 carbonate system is found have significant influence compared to other systems.

A mathematical model was developed by Haandel and Lettinga (1994)[1] to estimate alkalinity needed for maintaining the required pH in an anaerobic reactor treating sewage. The following assumptions were made, considering the pH range of 6.5 to 7.5

- Ammonia acts like a strong base and exists as ammonium
- Volatile acids-acetic and propionic are completely dissociated
- Ammonification produces alkalinity in the reactor by the reaction,

  $$RNH_2 + 2H_2O \longrightarrow ROH + NH4^+ + OH^- \text{ (ALK)}$$

  (Further assuming that quarter of raw sewage is organic nitrogen and conversion of 1 mol of TKN leads to formation of 0.071 meq/mg N)
- Volatile fatty acid removal leads to alkalinity increase if influent alkalinity is greater than effluent alkalinity

- Solubility of methane at partial pressure of 1 atm and 20 °C- 35 °C =1mmol/l
- Alkalinity of the system is equal to the bicarbonate concentration near neutral pH (Fig A 3)
- Equal concentration of CO_2 and CH_4 are produced on the digestion of 1g of COD

  i.e. 1/64 ml/g digested COD

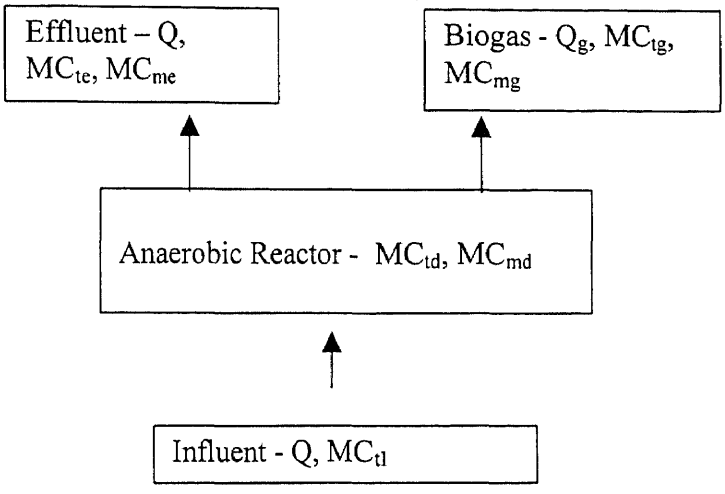

Figure 3.1 Flow of carbonate species and methane in an anaerobic system

where, C_t = carbonate species concentration (mol C/l)

C_m = methane concentration (mol C/l)

Q = waste flow (cu.m /d)

Q_g = biogas flow (cu.m/d)

i, e,d = influent, effluent and production in reactor

g = gaseous phase

M = daily mass flow (mol/d)

where, for carbonate species,

$MC_{tl} = Q * C_{tl}$

$MC_{te} = Q * C_{te}$

$MC_{td} = Q * C_{td}$

$$MC_{tg} = \frac{Q_g * \rho CO_2}{RT}$$

where, R and T are universal gas constant and standard temperature respectively

Considering methane species,

$MC_{md} = Q * C_{md}$

$MC_{me} = Q * C_{me}$

$$MC_{mg} = \frac{Q_g * \rho CH_4}{RT}$$

where, pCH_4 is the partial pressure of methane

Based on these assumptions, and conducting a mass balance on the figure above, the following relations were developed.

- $\rho CO_2 = ALK * 10^{(pK_{II} + pK_1 - pH)}$
- $\rho CO_2 = \frac{C_{ti} + C_{td} - C_{te}}{C_{ti} + C_{td} + C_{md} - C_{te} - C_{me}}$
- $\rho CO_2 = \frac{ALK_r * f_r}{K_H}$

Using the above relations, a quadratic expression was derived to estimate the alkalinity required to maintain a certain pH where,

$$ALK_r = \frac{0.5 * [b - (b^2 - 4ac)^{0.5}]}{a}$$

$$f_r = 10^{(pK_1 - pH)}$$

$$a = (1 + f_r)\, f_r$$

$$b = (C_{ti} + 2\, C_{ti} - C_{me})\, f_r + K_H (1 + f_r)$$

and $c = K_H (C_{ti} + C_{td})$

The details of other variables are given below.

ALK	alkalinity in the reactor as eq/l
ALK_r	alkalinity required as eq/l
K_H	Henry's constant
pCO_2	partial pressure of CO_2

CHAPTER 4

RESULTS AND DISCUSSIONS

The graphical user interface and database was developed using Microsoft VisualBasic 6 and Microsoft Access 97. The requirements were determined during the literature review and interface screens were built to accept detailed information from the user (operator) about the physical and operational parameters of the reactor and different characteristics of the wastewater as influent, reactor content and effluent. The application was capable of performing three different functions–

- Input/Edit –characteristics of influent, effluent and reactor contents (daily)
- Monitor – flow, pH, temperature and biogas production rate (measured every half hour by sensors and stored in database)
- Evaluate – current reactor condition

Information on the trends in observed characteristics were displayed in the form of graphs built using Active X controls. The application was then tested using sample values taken from the study of a full-scale UASB reactor operating in Pedregal, Brazil by Haandel and Lettinga (1994)[1].

Table 4.1 Physical characteristics of reactor [1]

Parameter	Value
Volume of reactor (cu.m)	160
Depth of reactor (m)	4
Area per inlet (sq.m /point)	2-4
Depth of separator (m)	1.3

Table 4.2 Average sewage characteristics for first 30 weeks of operation (HRT =17hr)[1]

Parameter	Average value
BOD (mg/l)	429
COD (mg/l)	799
Settleable solids (mg/l)	7.8
Total suspended solids (mg/l)	557
Total phosphorous (mg P/l)	8.2
Total Kjeldhal nitrogen (mg N/l)	59
NH_4^+ (mg N/l)	47
Alkalinity (meq/l)	7.9
Volatile fatty acids (mg HAc/l)	106
pH	6.8
Temperature (°C)	24

Table 4.3 Operational parameters of the reactor [1]

Parameter	Value
Influent flow (cu. m/d)	225
Hydraulic retention time (hr)	17
Solids retention time (d)	118.2
Upflow velocity (m/hr)	0.23
Applied COD load rate (kg /cu.m-d)	1.12
Applied BOD load rate (kg/cu.m-d)	0.60
Sludge discharge	Not applied

Based on the concentration of the biomass retained in the reactor and the details of the height of sampling ports, the application calculated the biomass inventory in the reactor as shown in table below.

Table 4.4 Calculation of biomass inside reactor

Height of sampling zone (m)		Cross–sectional area (sq.m)	Concentration of biomass (kg/cu.m)	Calculated total biomass in each zone (kg)
Zone1	0.3	40	38.5 *	462
Zone 2	0.45	40	35.8 *	644.4
Zone 3	0.5	40	32.5 *	650
Zone 4	0.5	40	5.5 *	110
Zone 5	0.5	40	2.75 *	55
Total mass of biomass in the reactor = 1921.4 kg				

*Assuming Volatile suspended solids = 0.55 times Total suspended solids

The reactor condition was evaluated using various aspects, which were selected as good indicators of digestion process from the information obtained through the background studies. The parameters chosen for process evaluation, their evaluation criteria and significance are given in the following table.

Table 4.5 Reactor Parameters and their evaluation criteria

Parameter	Evaluation condition
Hydraulic retention time, HRT (d)	Checked against design HRT
Solids retention time, SRT (d)	Checked against design SRT
Upflow velocity, UPVEL (m/hr)	< 1m/hr
Organic loading rate, OLR (kg/cu.m –d)	< 2 kg COD/cu.m-d
Temperature, T (°C)	- 0.6°C < Design Temp < +0.6 °C
pH in reactor	6.5 < pH < 7.5
Ratio- volatile fatty acids/ alkalinity	< 0.25
Ratio – MLVSS /MLSS *	0.55 < 0.8
Ratio – CH_4: CO_2 (%)	$CH_4 > CO_2$

*MLVSS – Mixed liquor volatile suspended solids (mg/l)
MLSS – Mixed liquor suspended solids (mg/l)

The design values for the operational parameters are based on the reactor physical features, wastewater characteristics, concentration of biomass to be held in the reactor, kinetics of microbial growth, etc to achieve the desired degree of treatment efficiency. The observed values for HRT, SRT, OLR and UPVEL were checked against the design values as values lower than design criteria can cause process failure. The hydraulic retention time (HRT) is an important operational parameter as it determines the period for which wastewater is retained in the reactor. Variation in inflow produces change in HRT and a value below the design HRT can result in wash out of biomass before sludge formation. The solids retention time (SRT) is the duration for which solids are held in the reactor. The design SRT represents the time required for adequate contact between microbes and organic matter for degradation. A lesser value of SRT than design value can result in washout of biomass reducing process efficiency. The observed organic

loading rate OLR is checked against the design value to determine if overloading or underloading of the reactor is taking place. Underloading reduces the organic matter available to the microorganism and results in a shift in the dominant microbial species population and formation of voluminous sludge, which can washout [3]. Organic overloading can increase the concentration of volatile acids produced by acid-formers in the reactor, which will be higher than the utilization rate of the same, by methanogens. This creates conditions unfavorable to the methanogens by lowering the pH thus leading to reactor failure. A value less than 0.25, for the ratio of the concentration of volatile acids to the alkalinity available in the reactor and the pH range between 6.5 and 7.5 ensures that the reactor is stable regarding acid formation and its consumption.

An upflow velocity greater than 1m/hr can break up already formed sludge particles while a value less than that ensures sufficient mixing in the reactor avoiding formation of dead zones [1,8]. Every microorganism has its optimum temperature but all activity ceases at temperature below 10 °C [3]. Temperature fluctuations more than 0.6 °C per day from the operating value can prevent methanogens from developing a stable population required for the process [16].

A change in the concentration of biomass can be immediately detected by checking the ratio of volatile suspended solids to total suspended solids against the desired range. A lower value can indicate loss of biomass and the operator can take remedial actions while a higher value indicates need for sludge discharge. Lower methane content in biogas indicates unfavorable reactor situation leading to suppression of methane formation. Besides this, the reactor contents are also tested for presence of

substances given in Table 2.5.1 at inhibitory concentrations as part of evaluating reactor situation.

The model described in the previous chapter by Haandel and Lettinga (1994) [1] for alkalinity estimation was used to predict the need for alkalinity addition based on the estimated effluent pH values. The details of the stimulation are given below.

1. Influent carbonate species, $Ct_i = 0.010$
2. Concentration of methane species in effluent, $Cm_e = 0.001$ mol/l
3. Alkalinity in the effluent, $Alk_e = 0.010$ eq/l

It can be seen from Figure 4.1, that the value of effluent pH drops with the increased concentration of digested COD. This is due to the formation of acetic acid produced by the digestion of organic matter. The alkalinity in the reactor is then used up to neutralize the increase in acid formation thus lowering its concentration. From the table shown above, in the first case the alkalinity present in the wastewater is sufficient to neutralize acid formed and hence the reactor pH remains in the desirable range of 6.5 to 7.5. As the concentration of digested COD increases, the pH value drops as a result of the alkalinity consumed. In these situations the influent alkalinity is not adequate and additional alkalinity has to be added.

The model can further be used to estimate the alkalinity required in maintaining a desired pH value. So the required alkalinity concentrations were calculated for maintaining different values of pH for a digested COD concentration of 3200 mg/l as shown in Figure 4.2.

It can be seen from Figure 4.2, that in order to maintain a pH of 6.5 at a digested COD concentration of 3200 mg/l an alkalinity addition of 899 mg/l as $CaCO_3$ and the

required alkalinity increases with increase in the value of pH to be maintained. Higher alkalinity in the reactor also increases the concentration of carbonate species in the effluent. This is because the alkalinity added binds with the carbondioxide produced to form bicarbonate. The increased concentration of carbondioxide in solution implies a lesser concentration in biogas, which is evident from Figure 4.4 as the decrease in partial pressure of CO_2.

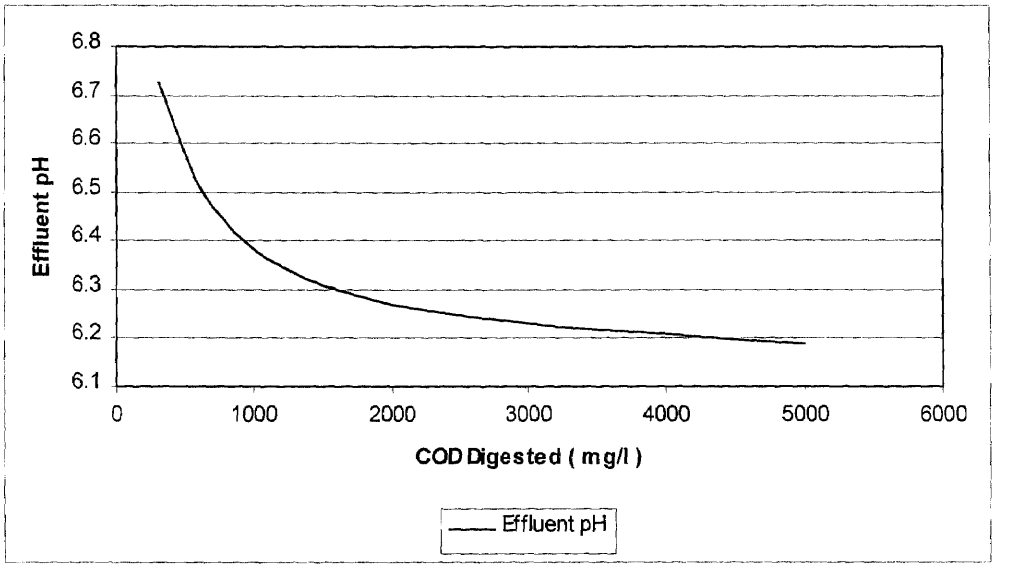

Figure 4.1 Effluent pH values for various concentrations of COD digested for an alkalinity of 0.010 eq/l present in the reactor at 25 °C

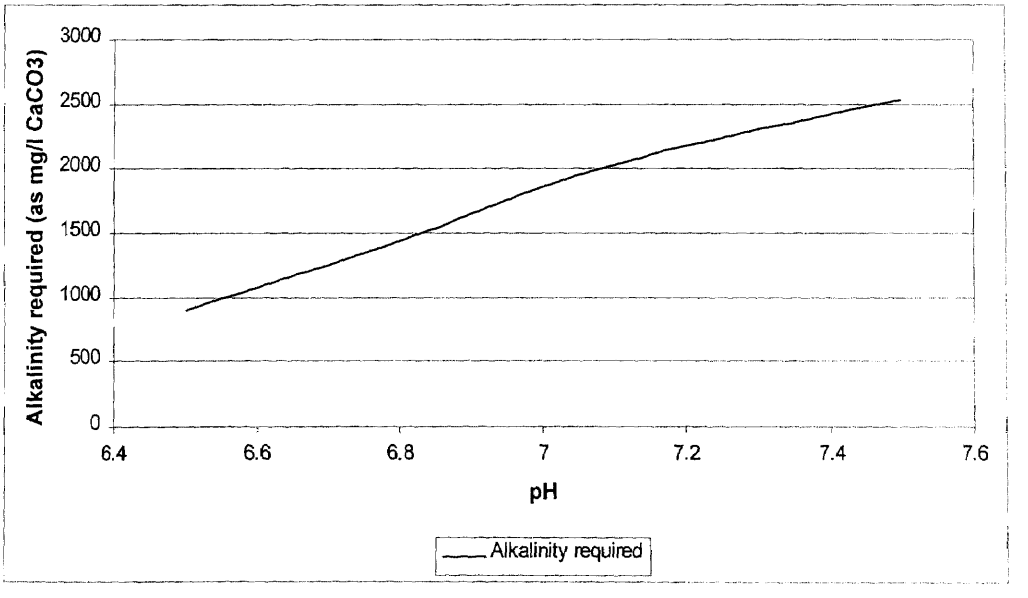

Figure 4.2 Alkalinity required for maintaining different pH at 25 °C, with an influent carbonate species concentration, C_{ti} = 0.01 mol/l, pK_1=6.35 and K_H= 0.033

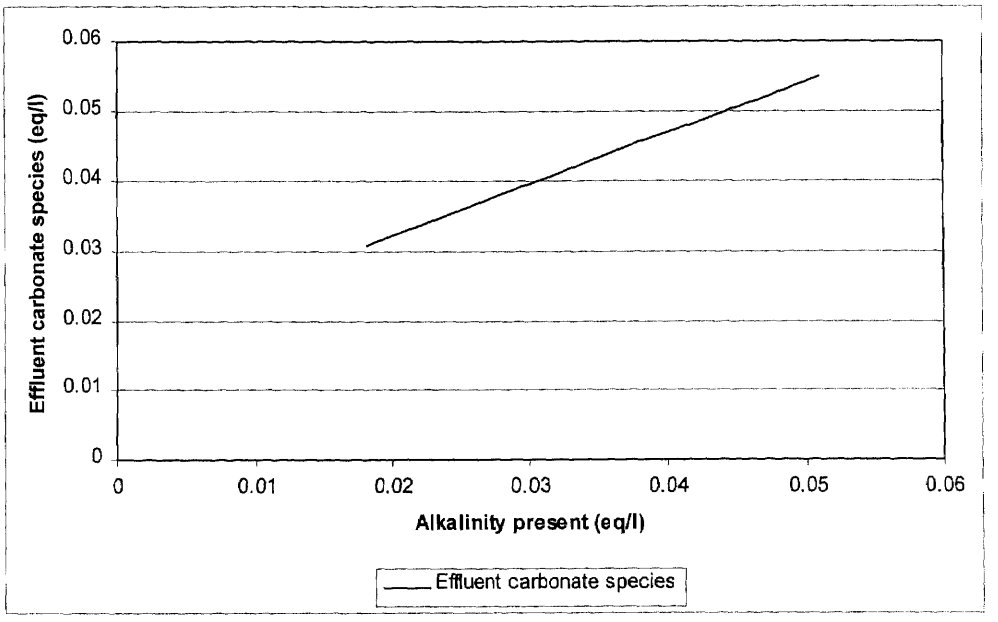

Figure 4.3 Effluent carbonate species concentration for various concentration of alkalinity added at 25 °C, with an influent carbonate species concentration, C_{ti} = 0.01 mol/l, pK_1=6.35 and K_H= 0.033

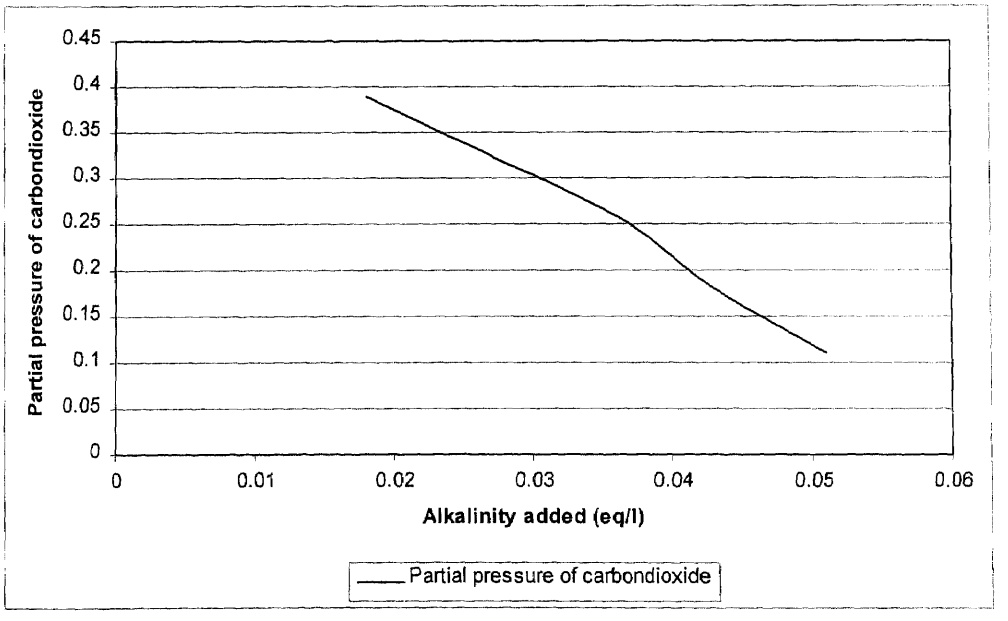

Figure 4.4 Partial pressure of carbondioxide for various concentration of alkalinity added at 25 °C, with an influent carbonate species concentration, C_{ti} = 0.01 mol/l, pK_1=6.35 and K_H= 0.033

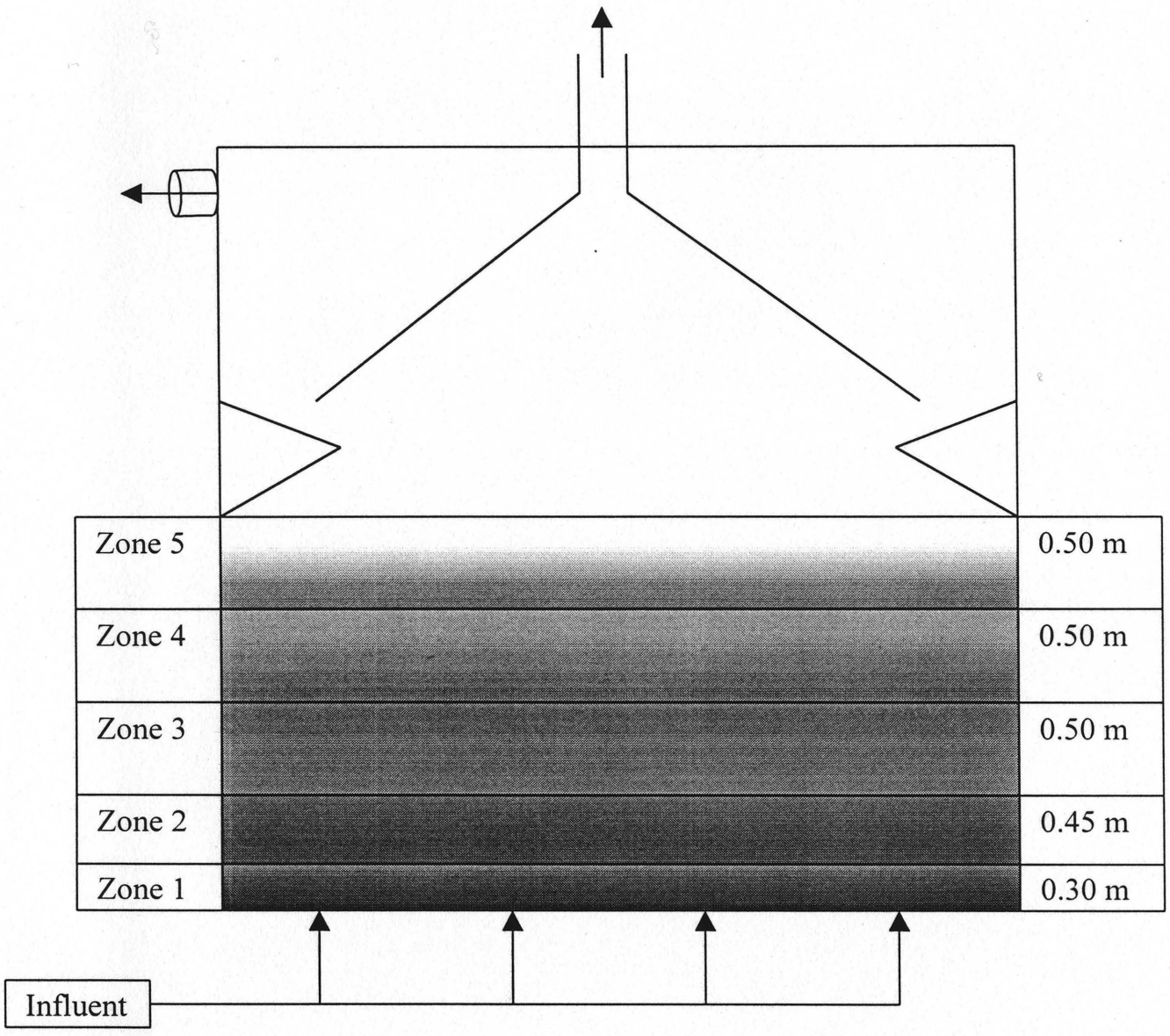

Figure 4. 5 Location of sampling zones in UASB reactor

CHAPTER 5

SUMMARY AND CONCLUSION

The treatment and disposal of waste generated in the community in the safest and most economical way is essential for ensuring public health. In the light of escalating costs and stringent regulations and with the rapid development in computers and process control engineering, introduction of intelligent process control into the treatment operation is a viable solution. The UASB process is a very popular anaerobic system used worldwide. Due to its capability to handle high organic loading rates and lesser operational costs, the system is an efficient mode of treatment for concentrated municipal and industrial wastewater and sludges.

The objective of this study was to create a human machine interface for the UASB process combining knowledge of process mechanism and computers. A graphical user interface was designed and developed to receive and store the detailed information about the reactor, and wastewater characteristics and evaluate the process stability based on this information. The literature review conducted revealed existence of intricate relationship between operational parameters and wastewater properties. Based on the literature review nine parameters including hydraulic retention time, solids retention time, upflow velocity, organic loading rate, temperature, pH, ratio of volatile acids to alkalinity, ratio of volatile suspended solids to total suspended solids and ratio of methane to carbondioxide content in biogas were selected as the parameters indicating reactor situation. These parameters were evaluated against the standard or allowable values obtained during literature review. The treatment efficiency, for a given reactor, waste and sludge formed inside the reactor

heavily rely on the operators skill in controlling the operational factors. The model for estimating alkalinity can be used to estimate alkalinity requirements based on wastewater characteristics.

Incorporation of more validated models for simulation and inclusion of additional features for acquiring and processing data can enhance the functionality of currently developed application. This will promote its use as a control and diagnostic tool for the improving operation of UASB reactors

APPENDIX A

pH-LOG CONCENTRATION DIAGRAMS

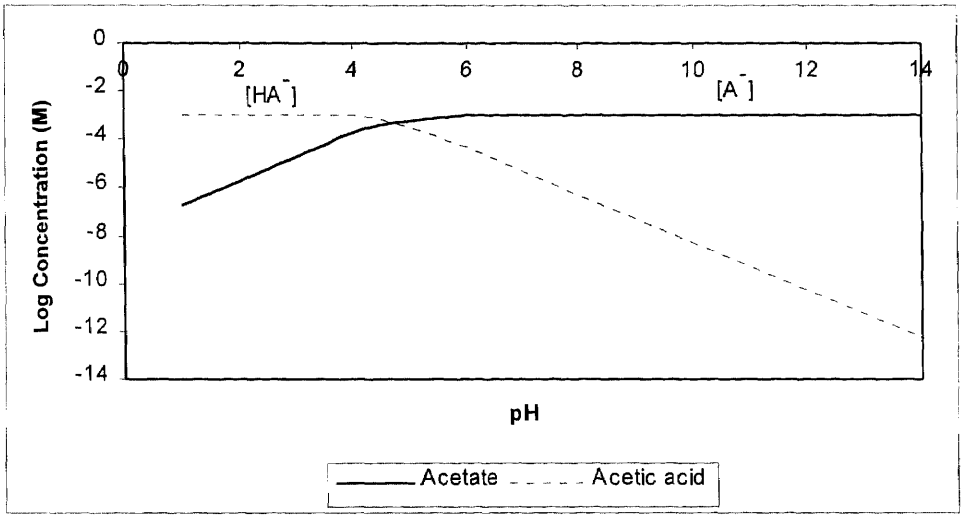

Figure A1 pH – log Concentration Diagram for 0.001M Acetic acid system at 25 °C [29]

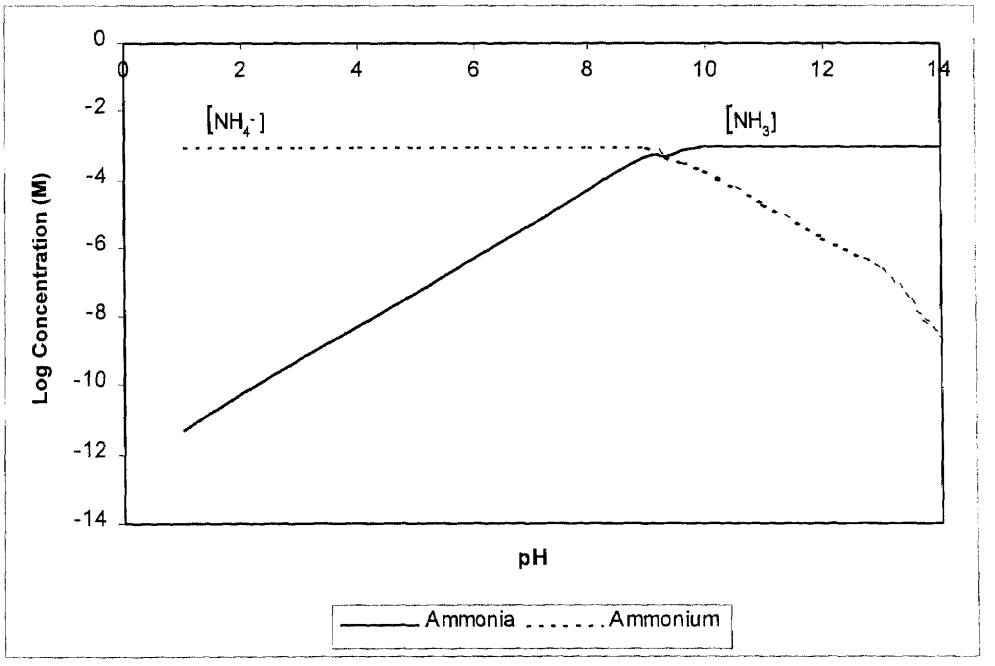

Figure A2 pH – Log Concentration Diagram for 0.001M Ammonia system at 25°C [29]

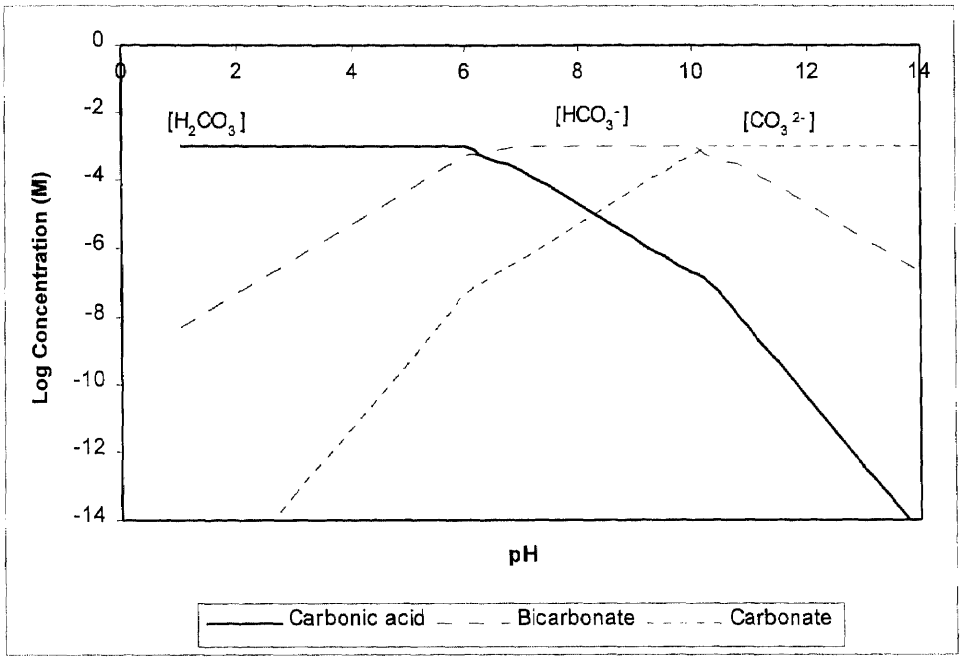

Figure A3 pH – Log Concentration Diagram for 0.001M Carbonate system at 25°C [29]

REFERENCES

1. A.C. Haandel and G. Lettinga, *Anaerobic Sewage Treatment*, John Wiley & Sons Ltd., New York, USA, 1994

2. T. Lawson, "*The UASB process*", Water, pp.11-12, October 1992

3. K.C. Lin and Z. Yang, "*Technical review on the UASB process*", International Journal on Environmental Studies, Vol.39, pp.203-222, 1991,

4. I. Mehrotra and S.K Narnoli, "*Sludge blanket of UASB reactor :Mathematical simulation*", Water Research, , Vol.31, No. 4, pp.715-726, 1997

5. B.K. Ahring and J.E. Schmidt, "*Granular sludge formation in UASB reactors*", Biotechnology and Bioengineering, Vol.49, 1996

6. M.A. Davlyatshina, S.V. Kalyuzhnyi, V.I.Sklyar, S.N. Parshina, M.V.Simankova, N.A.Kostrikina and A.N. Nozhevnikova, "*Organic removal and microbiolgical features of UASB reactor under various organic loading rates*", Bioresource Technology, Issue. 55, pp. 47-54, 1996

7. I.C. Tseng, H. Harada and S. Uemura, "*Effect of temperature elevation from 55℃ to 65℃ on the performance of a thermophilic UASB reactor and the characteristics of the Methanogenic granular sludge*", Environmental technlogy, Vol.16, pp.987-994, 1995

8. G.Tchobanoglous and F.L.Burton, *Wastewater Engineering- treatment, Disposal and Reuse*,Third edition, McGraw-Hill, New York , 1972

9. C.F. Forster, "*Anaerobic upflow sludge blanket reactors: aspects of their microbiology and their chemistry*", Journal of Biotechnology, Vol.17, pp.221-232, 1991

10. J.P. Guyot, A. Noyola and O. Monroy, "*Evolution of microbial activities and population in granular sludge frm an UASB reactor*", Biotechnology letters, Vol.12, No.2, pp.155-160, 1990

11. Z.I. Bhatti, K. Furukawa and M. Fujita, "*Microbial diversity in UASB reactors*", Pure and Applied Chemistry, Vol.69, No.11, pp.2431-2438, 1987

12. H.S. Shin and B.C. Paik, "*Improved performance of upflow anaerobic sludge blanket(UASB) reactors by operating alternatives*", Biotechnology Letters, Vol.12 No.6, pp. 469-474, 1990

13. A.J.B. Zehnder and W. Gujer, "*Conversion process in Anaerobic Digestion*",Water Science and Technology, Vol.15, pp.127-167, 1983

14. J.A. Eastman and J.F. Ferguson, "*Solubilization of particulate organic carbon during the acid phase of anaerobic digestion*", Journal of Water Pollution Control Fedration,Vol.53, No.3, pp.352-366, 1981

15. J.A.Eastman, "*Solubilization of particulate organic carbon during the acid phase of anaerobic digestion*", Ph.D Thesis, University of Washington, Washington, 1977

16. Water Environment Federation, *Operation of Municipal Wastewater Treatment Plants*, Vol .3, Fifth Edition,Virginia, 1996

17. C.Zickefoose and R.B.J.Hayes, *Operations Manual – Anaerobic Sludge Digestion*, United States Environmental Protection Agency, 1976

18. R.C.Dague, *Notes for CE-522- Water Pollution Control Process Analysis*, Iowa State University, Ames, Iowa, Spring 1990

19. V.L. Snoeyink and D.Jenkins, *Water Chemistry*, John Wiley and Sons, Inc., New Jersey, 1980

20. J.Parker, J.M. Martinko and M.T.Madigan, *Brock Biology of Microorganisms*, Prentice Hall, New Jersey, Eighth Edition, 1997

21. J.F. Kennedy, L.M. Sanchez, M.G. Roig, M.J.M. Rodriguez and J.M. Cachaza, *"Principles of biotechnological treatment of industrial wastes"*, Critical Reviews in Biotechnology Vol. 3, No.2, pp.99-116, 1993

22. C.Y. Lin, K. Sato, T. Noike and J. Matsumoto, "*Methanogenic digestion using substrate of acetic, propionic and butyric acids*", Water Research, Vol.20, No.3, pp. 385-394, 1986

23. A. Banerjee, P. Elefsiniotis and D. Tuhtar, " *Effect of HRT and temperature on the acidogenesis of municipal primary sludge and industrial wastewater*", Water, Science and Technology, Vol. 38, No. 8-9, pp. 417-423, 1998

24. M.W. Barnett, "*Knowledge-based expert system applications in waste treatment operation and control*", ISA Transactions, Vol. 31, No. 1, pp. 53-60, 1992

25. G.Olsson, "*Control of wastewater treatment systems*", ISA Transactions, Vol. 31, No. 1, pp. 87-96, 1992

26. A.F.M.V.Velsen, G.Lettinga, S.W. Hobma, W. D. Zeeuw and A. Klapwijk, "*Use of upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment*", Biotechnology and Bioengineering, Vol. XX11, pp. 699-734, 1980

27. S.G. Pavlostathis and E. G. Gomez, "*Kinetics of anaerobic treatment*", Water, Science and Technology, Vol. 24, No. 8, pp. 35-59, 1991

28. G.C. Cha and T. Noike, " *Effect of rapid temperature change on HRT on anaerobic acidgenesis*", Water, Science and Technology, Vol. 36, No. 6-7, pp. 247-253, 1997

29. A.W. Lawrence and P.L. McCarty, "*Kinetics of methane fermentation in anaerobic treatment*", Water Pollution Control Federation, Vol. 41, No. 2, Part. 2, pp. R1-R17, February 1969

30. C.M.M. Campos and G.K. Anderson, "*The effect of the liquid upflow velocity and the substrate concentration on the start-up and steady-state periods of lab-scale UASB reactors*", Water, Science and Technology, Vol. 25, No. 7, pp. 41-50, 1992

31. P.Sam-Soon, R.E. Lowenthal, M.C. Wentzel, R.E. Moosbrugger and G.V. R. Marais, "*Effects of a recycle in upflow anaerobic sludge bed (UASB) systems*", Water SA, Vol. 17, No. 1, pp. 37-46, 1991

32. B.T. Dudely, A.R. H. Graham, H.Isherwood and E.Senior, "*Laboratory-scale UASB digesters (with/without conditioning tank and recycle): Efficacy to treat increased hydraulic loads*", Water SA, Vol. 19, No. 4, pp. 313-318, 1993

33. L.D. Benefield, J.F. Judkin Jr. and B. L. Weand, *Process Chemistry for Water and Wastewater Treatment*, Prentice-Hall, Inc., New Jersey, 1982

34. G. Lettinga, J. Field, J.V. Lier, G. Zeeman and L.W. Hulshoff Pol, "*Advanced anaerobic wastewater treatment in the near future*", Water, Science and Technology, Vol. 35, No. 10, pp. 5-12, 1997