Gasification of dried sewage sludge using Bubbling fluidized bed gasifier for Syngas production

By

Muhammad Abdullah Khan

School of Chemical and Materials Engineering

National University of Sciences and Technology

May 2020

Gasification of dried sewage sludge using Bubbling fluidized bed gasifier for Syngas production

Name: Muhammad Abdullah Khan

Reg. No: 00000170872

This thesis is submitted as a partial fulfillment of the requirements for the Degree of

MS in Chemical Engineering

Supervisor Name: Dr. Salman Raza Naqvi

School of Chemical and Materials Engineering (SCME)

National University of Sciences and Technology (NUST)

H-12 Islamabad, Pakistan

May2020

Dedication

TO MY BELOVED FAMILY

Acknowledgements

All praises for Allah Almighty, the Most Benevolent, the Most Merciful, who granted me courage, strength and will power to carry out my work. It was He who helped me overcome all the obstacles in my work and I am utmost grateful for His help which enabled me to complete my work in allotted time.

My deepest gratitude to my supervisor, Dr. Salman Raza Naqvi, to whom I cannot thank enough for his dedication, help and support throughout my work. I am deeply thankful to him for believing in me. He was always there when I needed any kind of assistance.

I am extremely thankful to my co-supervisor, Dr. Zaib Jahan and my Guidance and Examination Committee (GEC) members, Dr. Muhammad Bilal Khan Niazi and Dr. Taqi Mehran, for their help and support on moral and material grounds. Their motivation kept me going and their help assisted me to complete this project.

My truthful thanks to all Lab Engineers who rendered every possible assistance in laboratory analysis pertaining to this task within the most befitting manner.

Good Friends are blessing of God, Gratitude is extended to my friends Uzair, Ovaid, Bilal, Rizwan and Inam. At the conclusion, I would mention with an immense pride and internal satisfaction, the unconditional love, support and constant motivation through thick in thin my beloved family and friends bestowed upon me during this journey. For sure, without a doubt I am absolutely nothing without the tap on the back and positive reception from them.

Abstract

Driven by the energy demand, the humanity has consumed the fossil fuels to the brink of depletion and in doing so, damaged the natural ecosystem by global warming. Due to increasing earth population energy demand rises exponentially. There is a need that attention must be shifted towards alternative resources of fuel that are renewable and sustainable such as biomass and domestic waste for energy production. Non-lignocellulosic biomass like sewage sludge is the most suitable alternative used instead of fossil fuels because this material has potential to produce syngas which is a mixture of Carbon monoxide and Hydrogen The current research emphasis on the gasification process of sewage sludge for syngas production and to examine the effect of Temperature and Air ratio by using laboratory bubbling fluidized bed gasifier.

The ultimate and proximate analysis of Sewage sludge is done for elemental composition and existed functional group is identified through FTIR analysis. The Effect of heating rate ($5°C/min$, $10°C/min$ and $20°C/min$) on thermal degradation behavior is studied by TGA technique.

The product gases are analyzed by GC-TCD. The effect of temperature and Equivalence ratio is optimized at $850^{0}C$ and 0.35 at which product gas LHV is high with high cold gas efficiency of 42.3% was obtained.

Table of Contents

Contents

List of tables

List of figures

List of acronyms

ABBREVIATIONS

SS	Sewage sludge
GY	Gas yield
FBG	Fluidized bed gasifier
FTIR	Fourier transform infrared spectroscopy
BFBG	Bubbling fluidized bed gasifier
ER	Equivalence ratio
MSW	Municipal solid waste
MC	Moisture Content
VM	Volatile matter
FC	Fixed Carbon
CC	Carbon Conversion
WWTP	Waste Water treatment plant
MBR	Membrane bio reactor
CV	Calorific value
ASTM	American Society for testing and Material
TGA	Thermo gravimetric Analysis
GC-TCD	Gas chromatography with thermal conductivity detector
MJ	Mega Joules
ICE	Internal combustion engine

SYMBOLS

C	Carbon	O	oxygen
H	Hydrogen	S	sulphur
N	Nitrogen		

Chapter 1

Introduction

1.1 Background

Fossil fuels have been playing a dominant role in energy generation on global level. The Consumption of fossil fuels sharply increased after industrial revolution and have been increasing. Until 19th century, only coal was major source for energy generation and after that crude oil became energy source followed by natural gas. In the 20th century crude oil became the major source of energy. In 2017, energy produced by natural gas was 34,700 TWh, crude oil 52,050 TWhwhile coal was used to produce 43,916 TWh of energy. The rise in requirement of energy resulted in greater consumption of fossil fuels. A report titled "Statistical Review of world energy" published by British Petroleum in 2019, according to which global production stats of oil, natural gas and coal for 2018 are summarized in table 1 that shows crude oil was highest consumed fossil fuel followed by coal and natural gas for energy generation [1].

Table 1*:* Fossil fuels production in 2018[1]

Fossil fuel source	Fossil fuel production
Crude oil	4473 million tons
Natural gas	3868 billion cubic meters
Coal	3917 million tons

As there are finite source of fossil fuels, it is thought that fossil fuels will be depleted. Liquid and gaseous fuel will run out in next 50 years while coal will last for approximately 150 years [2].Other than this reason that fossil fuels resources are limited, the exploitation of fossil fuels energy can be a root of frequent atmospheric concerns such as acid rain, greenhouse effect, ozone layer depletion and other pollution. The CO_2 emitted through fossil fuels subsidizes 84% of greenhouse

gas GHG to atmosphere [3]. The emission of such large amount of CO_2 in the atmosphere also a consequence in unadorned global warming. In order to compete with environmental pollution and to conserve fossil fuels, it is necessary that we must shift towards renewables and sustainable fuel resources such as different waste, lignocellulosic and non-lignocellulosic biomass to obtain energy.

Non lignocellulosic biomass like sewage sludge is the most suitable alternative to be used instead of fossil fuels as this material has the potential for syngas production along with tar and char. It can produce energy and fuel by thermochemical conversion which is most promising alternative technology to reduce harmful waste and hazardous environmental impact.

1.2 Syngas

Syngas is a combination of two gases i.e. Carbon monoxide and hydrogen and is abbreviation used for synthesis gas. It is produced during gasification of fuel at high temperature. Gasification of biomass or coal, reforming of coke in presence of steam and gasification using waste are example of production of syngas. It can be used to produce chemicals such as NH_3 and CH_3OH.[4]. A simple process diagram for syngas production is shown in figure-1[5]
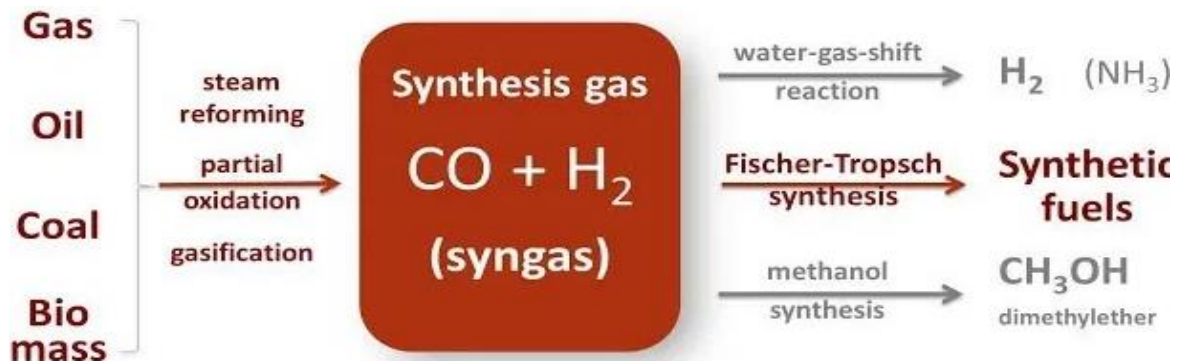
Figure 1: **PFD of Syngas [5]**

The average composition of syngas is as represented by table-2, varies depending upon raw material and operating conditions (Temperature, Air/fuel ratio, residence time) used in gasifier.

Table 2: **Syngas Composition [6]**

Serial No.	Syngas component	% Composition
1	Hydrogen	20-25
2	Carbon monoxide	15-30
3	Carbon dioxide	5-15
4	Methane	1-3
5	Nitrogen	40-50

1.3 Syngas Application

1.3.1 Integrated biomass gasification power plant (IBGPP)

- It is used in ICE for electricity generation
- It is used for the production of steam for electricity generation.

1.3.2 Chemical Synthesis

- Many chemicals like methanol, glycol can be made from syngas [7]

1.3.3 Benefits

- Waste conversion into fuels
- Economic power production
- Reduction in Carbon emission

1.4 Sewage Sludge

Sewage Sludge is a semi-solid left over by product of wastewater treatment plant. It is a mixture of inorganic and organic material and also contains microorganism. More specifically, SS is formed as a by-product of different stage of treatment of wastewater from industrial, commercial and domestic household effluents [8]. The Higher heating value of SS is almost same as fossil coal [9]. When entering to sewage treatment plants for the treatment, it contains about 1% waste water

and is digested an aerobically resulted to remove waste water from sludge. Figure 2 showing dried and crushed form of SS taken from NUST wastewater treatment plant

Figure 2: **Dried and crushed SS taken from NUST waste water treatment plant**

1.5 Production of Sewage Sludge

The amount of production of SS depends largely on volume of wastewater stream, population growth and method of treatment applied to waste water. Table-3 shows demonstrated statistics about quantity of sewage sludge production in 2014 by European state. It was reorganized in 2016.

Table 3: **Amount of Sewage Sludge production per day [10][11][12]**

Country	Amount of SS (tons/day)
China	95890
Switzerland	194500
Finland	141200
UK	136700
Poland	540300

France	896500
Germany	815600
Ireland	64500

1.6 Sewage Sludge as renewable fuel

SS is a blend of organic and inorganic compounds and leftover blend of proteins, lipids or fats. The advancement in technologies and increase in population brings about production of more human generated wastes and industrial wastes which can cause natural and monetary issues in regard to water, air and soil contamination. As indicated by Fytili et al. dried sewage sludge has a calorific value of 11−25.5MJ/kg [13]. Dry type of SS can be utilized as inexhaustible fuel because of such a high calorific value. It can possibly deliver bio-energy by utilizing thermochemical change procedures and this can likewise limit unsafe natural effect. The utilization of sewage sludge as sustainable power source assets is taken as healthier choice since this source can give around 10% of worldwide vitality stock [14]

1.7 Gasification of SS

Gasification is a unit process which transforms liquid or solid feed into gas fuel which can be further used to get energy by burning them. Gasification occurs at higher temperatures in the range of 650-900°C. It also requires a medium such as air, O_2 or CO_2 which directly affect the LHV of syngas. The main product of gasification is Char, Tar and combustible gases (Syngas).

Thermochemical conversion like combustion, pyrolysis and gasification is an attractive method of SS disposal. All these methods reduce the volume of SS and increase the energy content in efficient way. The energy content of gaseous product varies from 4-12MJ/m^3. The product gas is widely applied for heating purpose, power synthesis generation or various chemicals synthesis [15].

Out of above thermochemical conversion method, gasification of SS is recent trend as it produce less dangerous gases compared to other conversion methods with same amount of ash, so most of energy that remained in SS can be utilized to produce combustible gases mainly of syngas.

Gasification process involves following main steps

- Drying
- Pyrolysis
- Reduction
- Combustion

In gasification process biomass such as SS is first heated and dried after which pyrolysis reaction occurred. The major product of pyrolysis process are Char, Tar and gas which react with each other and with the gasification medium to give final Gasification products. The main products of gasification are syngas along with Carbon dioxide other hydrocarbon gases. All these products are results of different gasification reaction which takes place in gasifier.

The Schematic diagram for SS gasification is depicted below in Figure-3
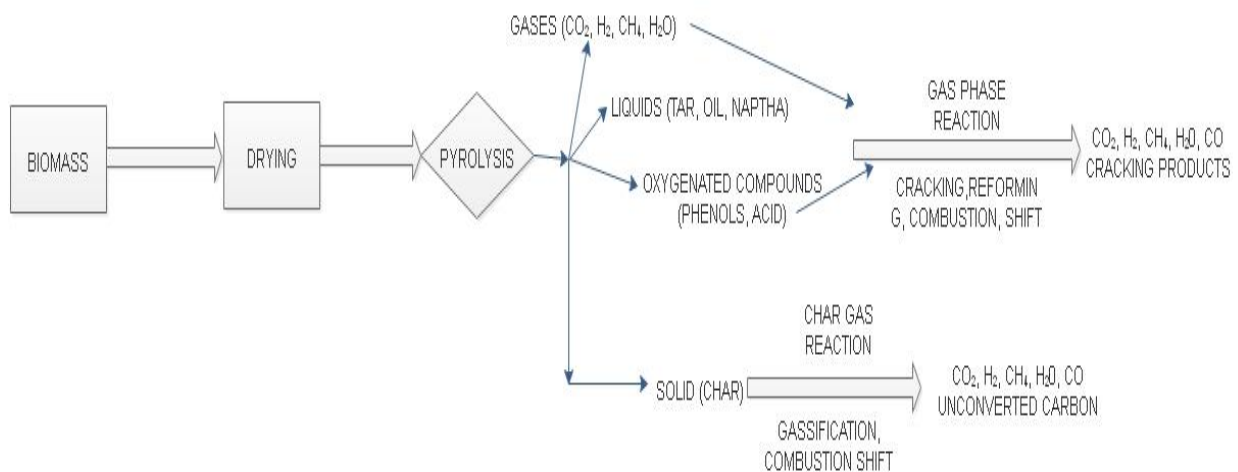
Figure 3: **Block diagram for SS gasification**

1.8 Gasifier and its types

The sequence through which reaction occurs in gasifier depends on type of gas-solid contact in gasifier. Different schemes of gasifier are available for gasification depending upon the feed entrance.

- Updraft
- Downdraft

- Fluidized bed

- Entrained flow

1.8.1 Updraft gasifier

The feed is entered from the top while the gases that are produced also exit at the top. At the bottom there is a grid by which gasifying agent is fed into it. The most commonly used gasifying agents are oxygen, steam or air after preheating. The gas rises in the gasifier through bed of in which fuel and ash descends down the reactor
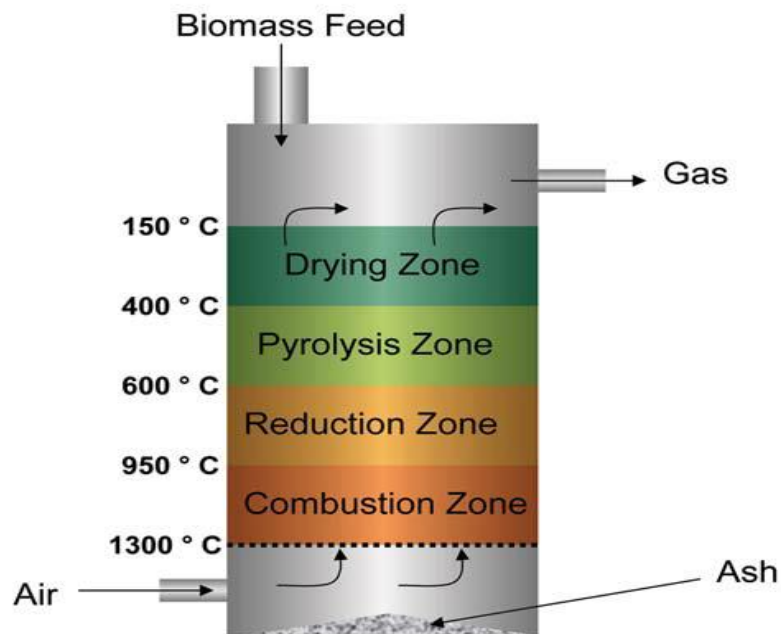
Figure 4; **Stages in updraft gasifier [16]**

The agent used for gasification such as air, oxygen that enters through the bottom of bed meets the char and ash descending from top. An exothermic combustion reaction occurs at the bottom because of high temperature and excess amount of oxygen.

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -393 \text{ kJ/mol}$$

The combustion reaction utilizes most of oxygen its amount decreases in upward direction converting combustion into partial oxidation and produces Carbon monoxide as product

$$C + \frac{1}{2}\,O_2 \rightarrow CO \qquad \Delta H = \text{-111 kJ/mol}$$
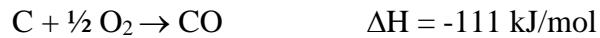
The mixture of hot gases and gasifying medium moves further in upward direction in gasification zone where char gasification reaction takes place. Here CO_2 is utilized in reaction hence its concentration decreases in this zone by following reaction.

$$C + CO_2 \rightarrow 2CO \qquad \Delta H = \text{+172.2 kJ/mol}$$

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H = \text{+131 kJ/mol}$$

These reactions are main reactions in gasification for production of Syngas. The temperature of the gas decreases as these are endothermic reactions.

Above gasification zone, pyrolysis of biomass takes place. In pyrolysis, the biomass converted into condensable and non-condensable gases along with char. The remaining heat dry the biomass that enters from the top.

1.8.2 Downdraft gasifier

In this type, feed is entered from top while gasifying agent such as air is introduced through nozzle from side of gasifier that combine with pyrolysis products. The energy needed for all the process such as gasification, pyrolysis and drying is supplied by combustion. The syngas exit from the bottom and tar content is low as compared to updraft gasifier. This helps in preventing cleaning process hence this type of gasifier is preferred for wide application
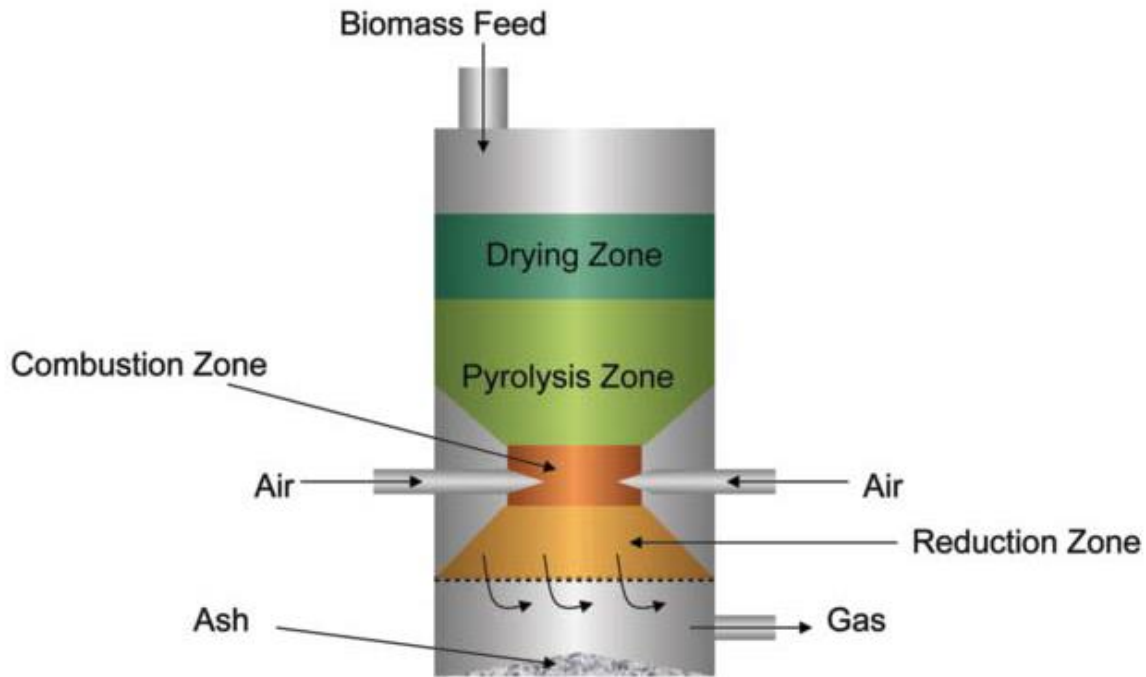
Figure 5: **Downdraft gasifier**

1.8.3 Fluidized bed gasifier

In this Fluidized bed gasifier, biomass is allowed to introduce from top while gasification agent is entered from the bottom, the gasifying agent serves for two purposes i.e. for fluidization of bed material and for reaction that occurs in the gasifier. The bed material is mostly consisting of Silica which is first heated to gasification temperature and provides uniform mixing with biomass.

There is limit of particle size and moisture content of fuel in such type. Mostly it is operated at less than 20% of moisture content. The maintenance of such type is relatively easy and operating cost is low compare to other types. One main benefit of applying bubbling fluidized bed gasifier is of uniform mixing that result in low residence time and low tar content.

As fluidizing gas enter in the bed, the fast-exothermic reaction takes place due to oxygen with char that uniformly mixed with the material of bed such as silica. The material of bed expands that release in heat to whole fluidized bed. As the gas rises the gasification reaction takes place.

These type of gasifier operates at temperature range of 800-1000°C so that agglomeration of ash can be avoided. This make it very useful for high ash fuel where there are chances for agglomeration of ash at high temperature.

Due to large thermal inertia and uniform mixing throughout the bed, these type can accept wide variety of fuels and especially attractive for biomass fuels.
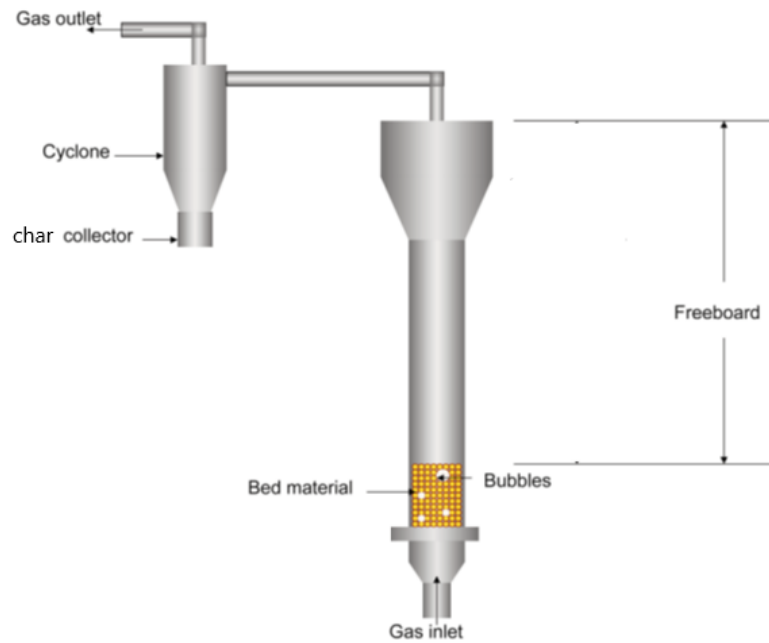
Figure 6: **Fluidized bed gasifier [16]**

1.8.4 Entrained flow gasifier

These type of gasifier are useful for IGCC plants and operate at a temperature range of 14OO^{0}C.

Here the gasifying medium is mostly oxygen into which powdered fuel is entrained.

Both the biomass and oxygen entered from side. The exothermic reaction takes place which increase the temperature above the ash melting point and results in decomposition of tar contents that produced in reactor. [17]
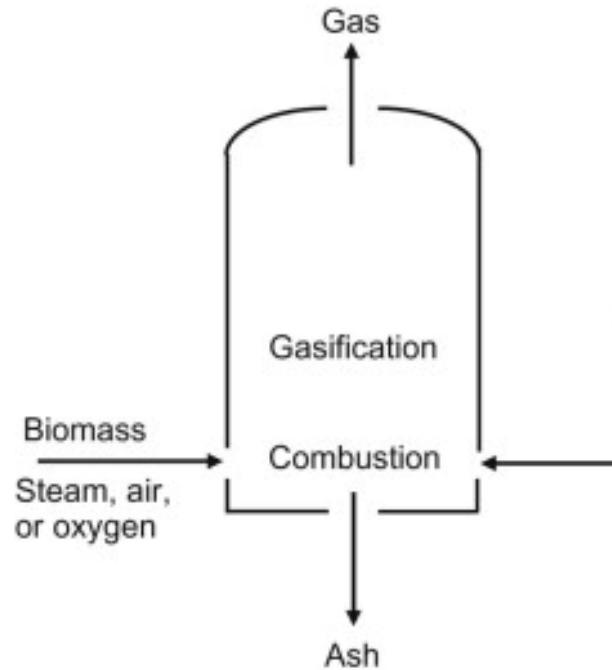
Figure 7: **Entrained flow gasifier**

1.9 Problem Statement

Pakistan is also among those countries in which proper disposal of sewage sludge is great problem. A high percentage of sludge is used in agriculture applications, combustion and land filling but these kind of disposal is not viable because of presence of heavy metal and pathogen in sludge. Among the process of treatment of sewage sludge, aerobic and anaerobic digestion has been employed on a large scale but these process are not much efficient and requires long time for its processing.

Thermochemical treatments are the other route by which sludge can be treated using gasification which is efficient and fast process and recover not only energy content but also minimize odor and destruct ingredients that are toxic and organic.

This research work is done to gasify sewage sludge to find optimum condition of temperature and ER ratio for obtaining high gas yield of higher heating values.

1.10 Research Objectives

- To collect and characterize sewage sludge to find out physiochemical properties
- To carry out gasification of SS in bubbling fluidized bed gasifier for production of syngas
- To study the effect of operating conditions such as temperature and Air/fuel ratio (ER) on product gas heating value, yield and cold gas efficiency of gasifier
- To find out optimum conditions at which gasifier can be operated more efficiently

1.11 Thesis outline

1st chapter delivers need of proposed topic, contextual and existing issues related to the topic. It also clarifies the definite terms, process, problem statement, objectives and scope of the strategic research work

2nd chapter will draft the literature survey accomplished to describe preceding efforts done on gasification of dried SS in BFBG for production of syngas and the effectof temperature and ER ratio on syngas heating value and efficiency of gasifier and to find out optimum conditions for this process.

3rd chapter contains the methodology associated to the sample preparation and characterization, gasification work and product gas analysis. It will also provide the related information about procedure and apparatus contributing in the experimental investigations.

4th chapter summarize results obtained form process and effect of operating condition on product gases. The results are discussed for better understanding of process. In this chapter, results are also concluded along with future recommendations.

5th chapter contains all findings and conclusions along with future recommendations.

Chapter 2

Literature Review

2.1 Introduction

To reduce volume of sludge and recover energy content efforts are made on production of syngas through thermochemical process. As discussed in previous section that gasification is promising process in this regard and have several advantages over other process like incineration.

For this purpose bubbling fluidized bed gasifier is selected which is best suitable for biomass or high ash fuel and it can take wide variety of fuel for its process

The current section evaluates the fluidized bed gasification of SS for the production of syngas and operating parameters temperature and ER on product gas.

2.2 Production of syngas in fluidized bed gasifier

Jun Dong et al. carried out the gasification of MSW in FBG. He studied the effect of operating parameters such as Air/Fuel ratio (Equivalence ratio) and Temperature on product gas. ER is defined as ratio of actual amount of oxygen fed to stoichiometric amount of oxygen needed for complete combustion. He suggested that ER is the main parameter for both characteristic of product and its distribution. According to him when ER increases then due to increase in oxygen the rate of oxidation reaction increases which ultimately increases the yield of syngas but decreases the LHV. The combustible gas yield is higher at low ER ratio but it decreases when ER ratio increases up to 0.4. Temperature also plays vital role in decomposition of reaction. His results shows an increasing trend of syngas as temperature of the system increases the syngas Lower Heating Value (LHV) but above 650°C there is decrease in LHV mainly due to reduction of CH_4 and C_2contents. To guarantee the process it was reported moisture contents of about 20-25% in fuel. The optimistic values at a temperature of 650°C and an ER of 0.4 were achieved. [18].

Werle et al. showed that producer gas components CO, H_2 and CH_4 in fluidized bed gasifier was increased by elevating the temperature and enhancing the O_2 concentration as gasifying agent.

In his conclusion he reported that drying temperature of sewage sludge has an effect on LHV of producer gas. The heating value of gases becomes low if temperature for dying of sewage sludge increases. An increase in particle size reduces the surface available for reaction. A set of experiment were conducted at various temperature and Equivalence ratio of 0.12-0.17 and the optimum value of Air/fuel of 0.18 was suggested for better results.[19]

Campoy et al. presented his work by using fluidized bed gasifier at temperature from 790-815°C with ER varied from 0.3 to 0.42 with the residence time of 1hr. Gasification was done using dried sewage sludge and it was reported that LHV of producer gas increases with the increase of temperature because of higher fuel conversion due to decomposition reaction. The increase in ER decreases the LHV due to enhanced oxidation reaction but it was observed that GY of dry sewage sludge shows an increasing trend. Carbon conversion defined as a ratio of gas flow rate in produced gas to mass flow rate of carbon fed with fuel is low for dried sewage sludge. This CC increases as ratio of air in the reactor increases. The highest carbon conversion was found at ER ratio of 0.25-0.4. It was also reported that gasification of high ash fuel is difficult because of sintering and agglomeration of ash, for this purpose improvement is needed for removal of ash from the system and disposed off properly [20]

Calvo et al. identified characteristic of SS in BFBG by taking different particle size of sewage sludge up to 200 mesh. Alumina silicate was selected as bed material. SS was fed into reactor at flow rate that is controlled by screw feeder. Gasification takes place at various temperature ranges with different air ratio. The product gas entered in cyclone which separated fly ash and char from gas followed by condenser. Producer gas is then allowed to pass through filtration unit to obtained clean gas for sample testing. Samples were collected at regular interval for GC. Producer gas with high quality was produced as a result with overall heating value of 8.4 to 9.4 Mj/Nm^3 which is low in tar content and with good cold gas efficiency of 57% [21]

Joan J. Manya et al. used dried and granular sewage sludge taken from urban WWTP. Experiments were performed in lab scale BFBGat atmospheric pressure with a continuous feeding of SS and air. The flow rate of biomass set to 1.2-10g/min with a constant bed height of 150 to 200mm. The bed is heated with electrical furnace. Flow rate of air was controlled by Rota meter. Entrained particles in gas were separated in cyclone and collected in char collector. The results showed that

efficiency of gasifier was increased by increasing bed height. Increasing air ratio result a decrease in concentration of syngas and also tar contents. [22]

Table 4: **Proximate and Ultimate Analysis of Sewage Sludge[18][19][20][21][22]**

Author Year	Proximate Analysis wt%		Ultimate Analysis wt%		LHV MJ/kg
Dong 2016	Moisture	9.2	C	48.3	15.5
	Volatiles	73.8	H	6.4	
	Fixed Carbon	12.8	O	28.2	
	Ash	4.2	N	0.8	
			S	0.3	
Author Year	**Proximate Analysis wt%**		**Ultimate Analysis wt%**		**LHV MJ/kg**
Werle 2014	Moisture	5.3	C	31.79	12.96
	Volatiles	51	H	4.36	
	Fixed Carbon	---	O	57.07	
	Ash	36.5	N	4.88	
			S	1.67	
Author Year	**Proximate Analysis wt%**		**Ultimate Analysis wt%**		**LHV MJ/kg**
Campoy 2013	Moisture	8.6	C	50.95	12.3
	Volatiles	51.8	H	7.3	
	Fixed Carbon	5.1	O	31.8	
	Ash	43.1	N	7.9	
			S	2.05	

Author Year	Proximate Analysis wt%		Ultimate Analysis wt%		LHV MJ/kg
Calvo 2013	Moisture	7.9	C	36.2	13.2
	Volatiles	55.1	H	4.5	
	Fixed Carbon	7.1	O	14.7	
	Ash	37.9	N	5.6	
			S	1.1	
Author Year	Proximate Analysis wt%		Ultimate Analysis wt%		LHV MJ/kg
J.Manya 2006	Moisture	8.9	C	55.3	10.26
	Volatiles	42.3	H	6.7	
	Fixed Carbon	6.7	O	28.1	
	Ash	42.1	N	8.2	
			S	1.8	

Table 5: **Examination studies of Sewage Sludge Gasification using bubbling fluidized bed gasifier [18][19][20][21][22]**

Author Year	Temperature ^{O}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4	LHV (MJ/Nm^3)
Jun Dong 2016	550	0.4	3.2	5.9	14	1	3
	650	0.4	4	7	14.2	2.5	4
	750	0.4	4.2	9.8	15	2	3.2
	850	0.4	4.3	11	15.1	1.2	3
	650	0	5	9	5	3.2	6
	650	0.2	5.3	10	14.4	3	5.5
	650	0.4	4	7	15	2.9	4.5
	650	0.6	3.2	6	16	2	2.5

Author Year	Temperature ^{O}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4	LHV (MJ/Nm^3)
Werle 2014	650-850	0.12	5	23	16	3	4
		0.18	4.5	30	14.9	1	4.9
		0.23	5.1	28	16.1	1	4.3
		0.27	5	20	16.3	1	3.9

Author Year	Temperature ^{O}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4	LHV (MJ/Nm^3)
Manuel Campoy 2013	790	0.3	8.4	9.9	15.4	5.1	1.07
	807	0.34	10.2	8.3	16.2	6.6	1.37
	815	0.42	9.4	7.3	16.4	4.6	1.42
	800	0.3	16	10	15	5	4
	800	0.34	10	8	17	7	3.2
	800	0.42	9	7	18	4	3.1

Author Year	Temperature ^{O}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4
Calvo 2013	750-850	0.2-0.4	20.7	13.4	11.1	6.7

Author Year	Temperature ^{O}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4
Joan.J		0.24	6.9	9	5.3	2.8

Mania 2005	650-850	0.28	5.1	8.5	15.8	2.65
		0.32	4	7.9	16.1	2.53
		0.36	2.5	7.2	16.5	2.4

Chapter 3

Material & Methodology

3.1 Raw material

The sewage sludge was gathered locally from a MBR domestic wastewater treatment plant located in the NUST, Islamabad. The sludge sample was first air dried to remove moisture present on surface. The dried SS sample was then placed in an electric oven for a day at 105±5°C until the constant weight was obtained to remove the inbound moisture contents. The sample is then crushed with mortar and pestle. Drying of SS highly effect CV and is necessary part before the start of characterization. The crushed sample was sieved through 500-600μm screen and finally stored in airtight bags.
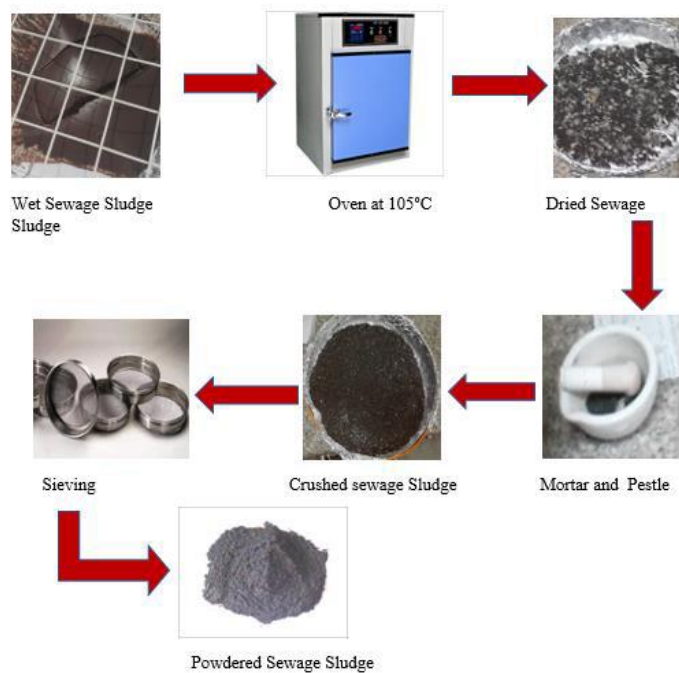

Figure 8: **Drying and crushing of sewage sludge**

3.2 Characterization of sewage sludge

3.2.1 Proximate analysis

Proximate analysis of SS was performed to check the amount of Moisture content, Volatile Matter, Fixed Carbon, and ash contents according to ASTM standards. Muffle furnace and electric oven were used for this purpose.

MC was determined by following ASTMD 3173, ASTME 871 method using simple oven [21]. The sample was first weighed to 1g and then dried in air atmosphere at 105^0C in an oven until constant weight was obtained within 24 hours. Following equation 3.1 is used to calculate percentage moisture content in sample

$$\text{MC\%} = \frac{M2 - M3}{M2 - M1} * 100 \qquad (3.1)$$

Where,

M_1 represents mass of the empty crucible with lid

M_2 represents mass of crucible, lid and sample before heating

M_3 represents mass of the crucible, lid and residue after heating

For Ash contents, sample weighed approximately 1 g each, dried at 103^0C and analyzed. Ash content present was calculated at 575^0C for 2 hours in atmospheric conditions using muffle furnace.

VM represents the mass loss in material, deducting that due to MC, when a sample is heated without presence of air under specific conditions. To remove VM, fused silica crucible was used and sample is heated at 900°C for 7 min. After heating, the crucible with residues was weighed again at room temperature. The loss in mass due to MC was also subtracted to find out net mass loss.

To calculate FC contents, following equation was used

FC(%) = MC (%) – VM (%) – Ash (%)

Table 6: **Equipment and condition for proximate analysis**

Components	Instrument	Temperature/time
Moisture content (MC)	Electric Oven	105^0C for 24 hrs
Ash Contents	Muffle furnace	575^0C for 2 hrs
Volatile Matters (VM)	Muffle furnace	900^0C for 7min
Fixed Carbon (FC)	FC(%) = MC (%) – VM (%) – Ash (%)	

3.2.2 Ultimate analysis

Ultimate analysis was performed to check presence of C, N, H, N and O. It is achieved through CHNS elementary analyzer (PerkinElmer 2400II, USA)

The high calorific value was found using Bomb Calorimeter according to given ASTM standards [23].

The High Heating Value (HHV) designates the amount of energy to be progressed from the sewage sludge sample. Salam et al. told in his study that the tentative measures to determine the HHV contain significant flaws so numerous correlation model equations were established to measure the HHV [24].

Figure 9: **CHNS elemental analyzer (PerkinElmer 2400II, USA)**

3.2.3 FTIR of Sewage Sludge

Chemical functional group in the SS sample was examined by means of PerkinElmer spectrum 100 FT-IR Spectrometer. Pellets of sample were made with KBr in 1:100 ratio. The resolution was kept at 4cm^{-1}. The IR scanning range was 400 to 4000cm^{-1}. Fourier transform is termed for this type of spectroscopy because the spectra obtained through this spectroscopy are based on Fourier transform mathematical process. This is used to achieve the qualitative and quantitative analysis of material

In FTIR technique IR radiations intermingle with the sewage sludge pellet with KBr. Some radiations are captivated by the sewage sludge sample and some are transmitted through sewage sludge. Based on absorbed and transmitted radiations, attained spectrum is known as FTIR spectrum. The subsequent spectrum generates a finger print of the sludge sample, used to identify the functional group.

The covalent bonds are elastic and remain continuously in vibration. Vibration could be bending or stretching. The vibrational motion influenced by these molecules is the appearances of their particular atoms. All organic compounds are capable of absorbing IR which matches to their vibration. IR spectrum is a graph between percentage transmittance and wave number in cm^{-1}
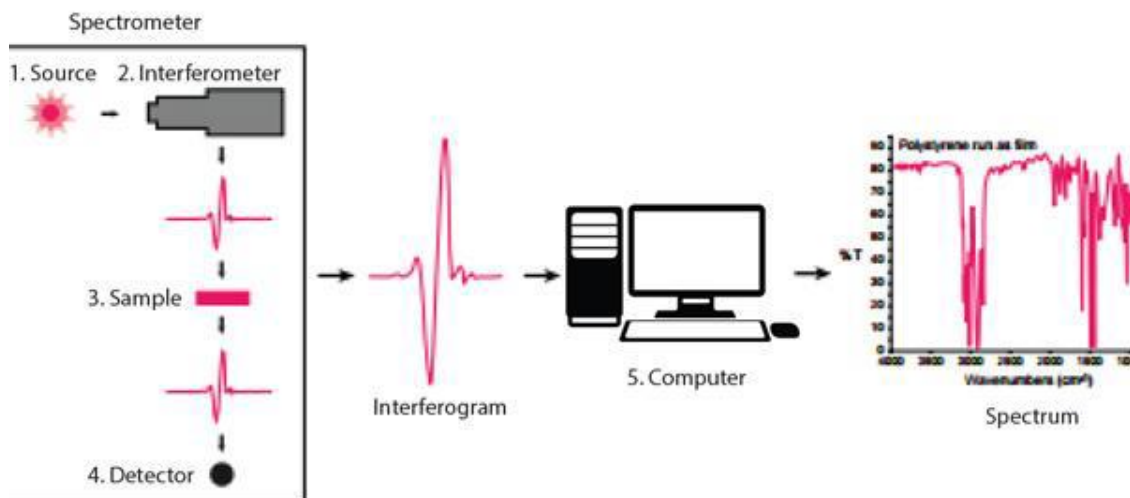
[25].

Figure 10: **Working principal of Fourier transform infrared spectroscopy**

3.3 Thermal Degradation Behavior of sewage sludge through TGA

The TGA of SS was determined by using thermo gravimetric analyzer under nitrogen environment. The temperature was kept in range of 25-800°C with nitrogen flow rate at 200ml/min. Initial mass of SS sample was 10±3mg.The mass loss and rate of mass loss was determined with respect to temperature and time at heating rate of 5, 10 and 20°C/min. To overlook heat transfer restriction, the slow heating rate was selected. The experiment was performed thrice to minimize error and maximize the accuracy. The results of TGA were useful in understanding the thermal decomposition behavior, reaction kinetics and thermodynamic parameters of SS gasification.

Thermo gravimetric analyzer contains a pan positioned in an incinerator. This pan is braced by a delicate electronic balance. The sample is placed onto the pan with a predefined heating rate and a temperature range at which changes is in sample is to be detected is given to the incinerator. The incinerator is heated from a lower temperature and reaches the maximum temperature and then it is cooled. The mass loss is observed during the entire process. The atmosphere of the incinerator is controlled by nitrogen or helium as an inert gas. The data obtained from TG analysis of the sewage sludge permits the interpretation of loss of volatile components in sludge, its thermal steadiness, and disintegration. The data attained is graphed among temperature range on abscissa and percentage loss of mass on ordinate [26].
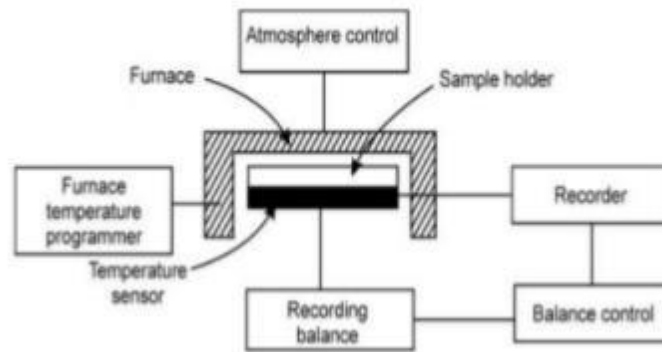
Figure 11: **Working principal of TGA [26]**

3.4 Experimental method for gasification

The reactor applied for SS gasification, which is depicted below in Figure-12, is an atmospheric pressure rig with 168mm diameter and 1071mm in length at which K-type thermocouple is attached for measuring temperature. The experiments reported here were conducted in electrically heated bubbling fluidized bed gasifier operating at atmospheric pressure. Silica sand is used as a bed material after sieving to a size fraction of 400 to 500micrometer. It is placed into gasifier after weighing to 400g. Air is used for both fluidization and reaction. The fluidization velocity is kept constant at $0.2ms^{-1}$.

The SS was first dried and moisture content was found by oven-dried method. It was reported about 6.5% moisture in sample. The dried SS was crushed to about 600micrometer and fed to the reactor from hopper of 200mm in diameter and 275mm in length at a controlled feed rate of 16.6g/min using screw feeder driven by variable speed stepper motor. Fuel metering was controlled by the speed of the motor. The sample is gasified at temperature of $700\text{-}850^0C$, as a result of which producer gases, char and tar are produced. Air was used as fluidizing medium. The air to fuel ratio was set at 0.2-0.4 with flow rate of 2.71L/min. The compressed air is allowed to enter in gasifier bottom for fluidization at a controlled rate through Flow meter that is attached. The air entering temperature was set to $250\text{-}300^OC$ by means of heat exchanger and metered by using rota meter.

A cyclone having 88 mm in diameter and 436 mm in length is situated past the horizontal pass. The purpose of cyclone is to separate the particles from the gas to pass through exit point. A thermocouple is also attached.

Tar is produced in heat exchanger after condensation of condensable gases. This is done in 88mm diameter and 700mm length of a condenser.

The produced gas after condensation passed through a filter of 61mm in diameter and 557mm in length and collected in gas bags. Sample is analysed for gas composition using gas chromatography.
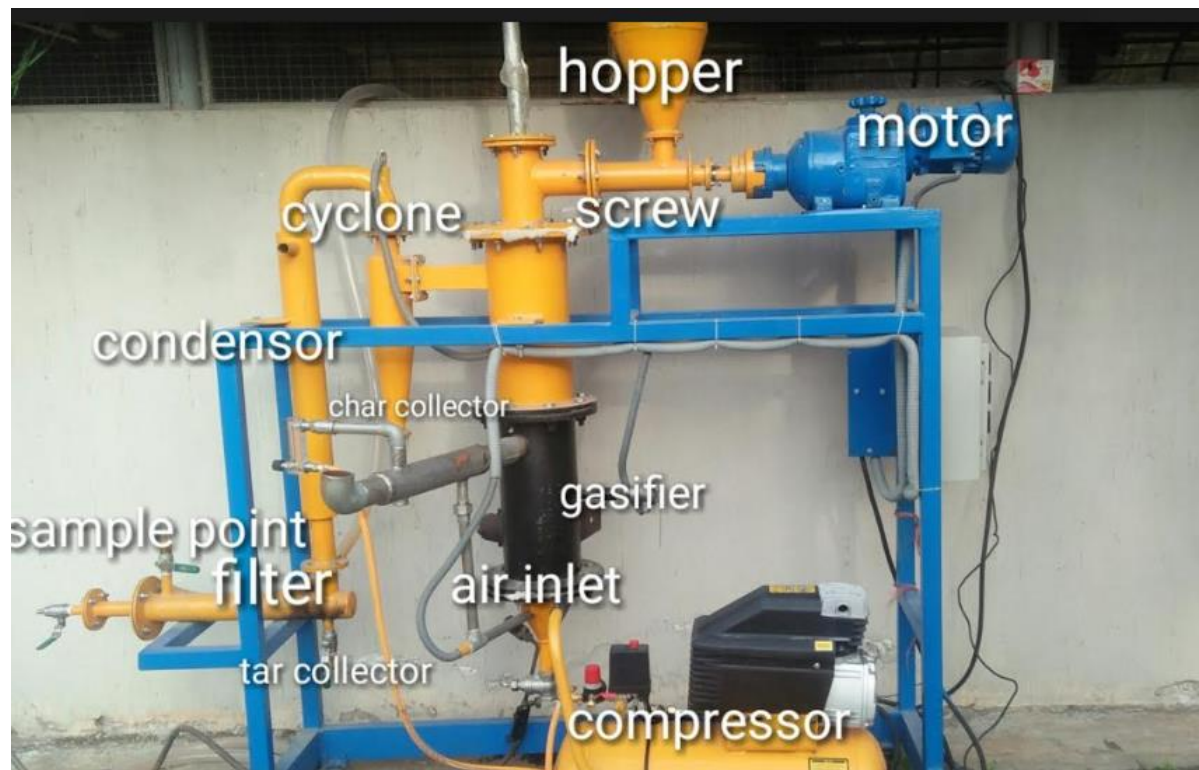

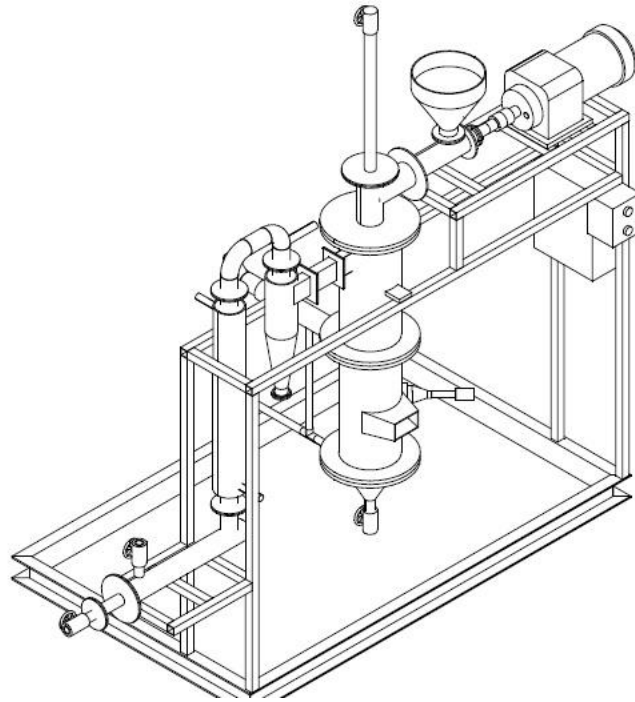Figure 12: **Process flow diagram of bubbling fluidized bed gasifier**

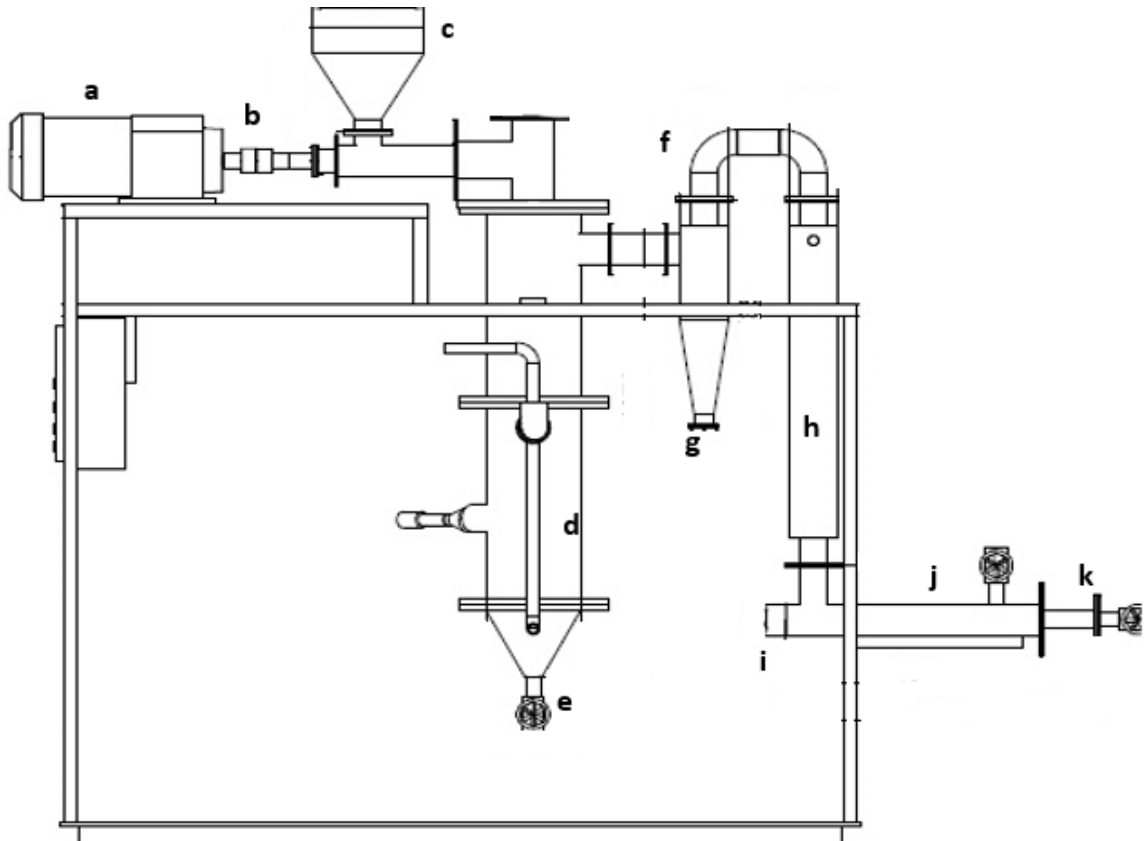Figure 13: **Schematic Diagram for bubbling fluidized bed gasifier**

Figure 14: **Process flow diagram of bubbling fluidized bed gasifier**

a) Motor

b) Screw feeder

c) Hopper

d) Gasifier

e) Air inlet

f) Cyclone Seperator

g) Char collector

h) Condenser

i) Tar Collector

3.5 Gas Chromatography with TCD detector of Gaseous Product

The Product gases obtained from gasification unit were collected in a gas bags from nozzle at the end of the filter so that gases could be collected without encountering environmental air. These gaseous samples obtained at 700°C, 750°C,800°C and 850°C were analyzed in an SHIMADZU GC-2010 Plus gas chromatograph attached with a TCD detector. An RT Molecular Sieve 5A, with ID 15224 having 30m length and 0.32mm ID. The column film thickness was 30μm with maximum temperature at 300°C. The temperature of oven was initially at 35°C and equilibrium time was 3min. Helium with flow rate of 20mL/min used as carrier gas. The injector temperature was 80°C and detector temperature was 220°C. The TCD was standardized with a typical gas mixture after specific period.

Figure 15: **SHIMADZU GC-2010 plus gas chromatograph with TCD detector**

Figure 16: **Collection of product gas in gas bag**

Chapter 4

Results and Discussion

4.1 Characterization of sewage sludge

4.1.1 Proximate analysis of sewage sludge

The proximate analysis of sewage sludge sample is depicted in Figure-17. The SS sample contained higher percentage of volatile matters 43.5% and ash 43.2% on dry basis but it has lower percentage of moisture 7.5% and fixed carbon 5.8% on dry basis. These proportions of volatiles in sample favors for thermal degradation processes because desirable products could be obtained by utilizing such material. Lower percentage of moisture content <10% suitable for gasification process. Ash contains a certain amount of Fe, Ca, Mg and K which can be used activated catalyst for the gasification reaction [27].
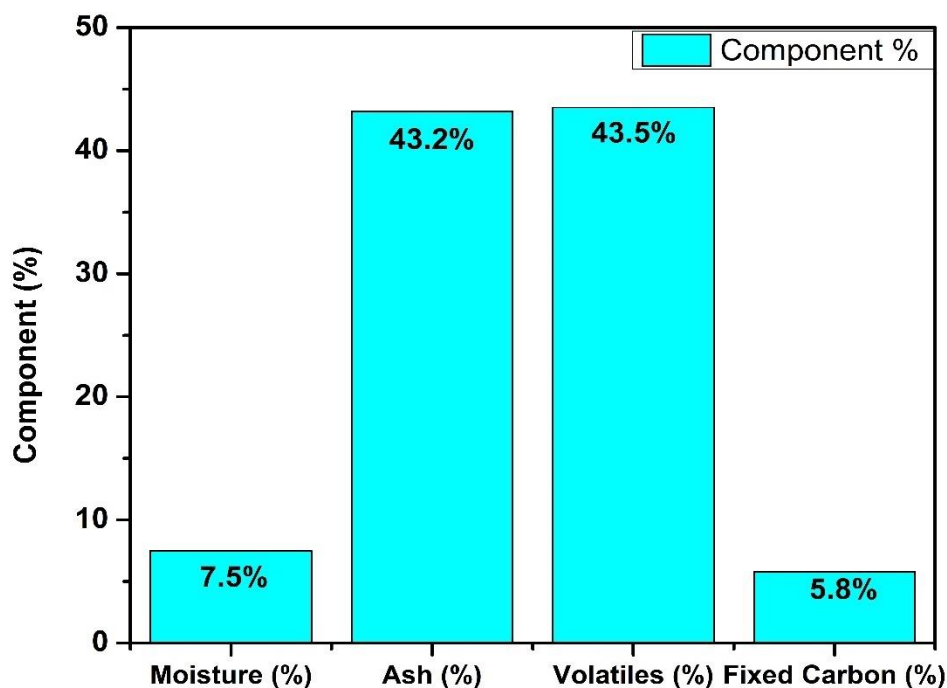

Figure 17: **Results of Proximate Analysis of sewage sludge**

4.1.2 Ultimate analysis of sewage sludge

The ultimate analysis of SS sample which illustrated the chemical composition of sample is displayed in Figure-18. The sample has higher percentage of oxygen contents (O) 45.1% and carbon content (C) 41.4% on dry basis but it contained lower percentage of hydrogen (H) and nitrogen (N), 6.6% and 6%, respectively. It also has very slight percentage of sulfur 1%. Xinyang et al. performed ultimate and proximate analysis of sludge and indicated the larger fraction of volatile matters 60.34%, ash 33.43%, carbon 36.88% and oxygen 52.01% and lower percentage of moisture 5.1%, fixed carbon 1.13%, hydrogen 4.94% and nitrogen 5.03% [28]Werle et al. performed ultimate analysis on sewage sludge and showed that the sample contains carbon 31.79%, Hydrogen 4.36%, Oxygen 57.07%, Nitrogen 4.88% and Sulfur 1.67% [29]
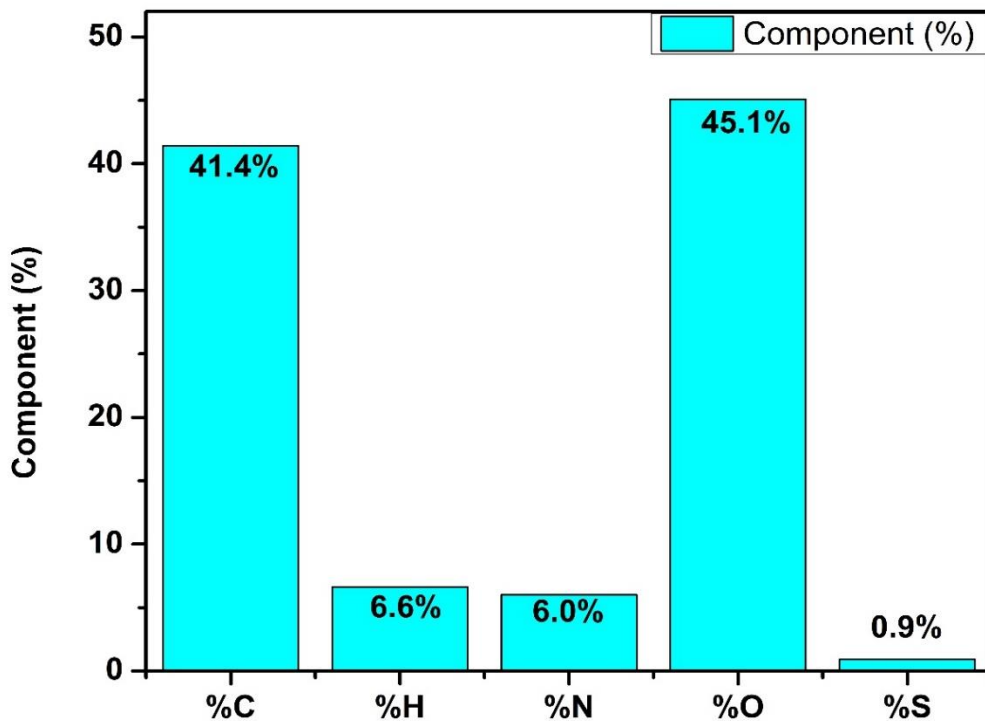

Figure 18: **Results of Ultimate Analysis of sewage sludge**

The calculated low heating value of SS sample was 15.6MJ/kg. The heating value of sample primarily depends upon the percentage of MC present in it. When sample contains lower moisture content its heating values becomes greater. The moisture free sewage sludge sample usually contain heating values range from 5-20 MJ/kg [30].

Jing-pei Cao et al. and Wu Zuo et al calculated higher heating value of sewage sludge obtained from WWTP with the help of bomb calorimeter and diverse types of formulas and developed correlations which was 16.24 and 10.4 MJ/kg [31].

4.1.3 Fourier Transform Infrared Spectroscopy (FTIR)

To comprehend the connection between the gasification performance and chemical structure of SS sample obtained from municipal WWTP, the disseminations of numerous functional groups and types of bonds (single, double or triple) were perceived by FTIR analysis. FTIR spectra of sewage sludge sample was shown in Figure 19

The spectrum for sewage sludge sample exhibited a very broad and strong transmittance peak at 3428.44 cm^{-1} which identified the presence of O-H stretching vibration because in the range of 3650-3200cm-1 O-H or N-H stretching occur[32] Next assigned peak was at 2821.81 cm^{-1} which identified the C-H regular and irregular Stretching vibration due to presence of aliphatic compounds. The range from 3300-2700cm^{-1} is specific for C-H stretching.

A strong peak was also detected at 1000 cm^{-1} which shows stretching vibrations of the C=O and C–O–C groupsThe C=O group identified the presence of acids and aldehydes. Ma et al. and Zhao et al. detected absorption band at 1549 cm-1, 1656cm-1 and 3420 cm-1 for primary and secondary amide group and O-H functional group, which provided the evidence of the presence of certain amount of protein in sludge sample [33].

The aromatic ring bending are categorized in the range of 750–875 cm-1.The range of 470–700 cm^{-1} is assigned for bending vibration of oxygen containing functional group with N, S and P respectively [34].
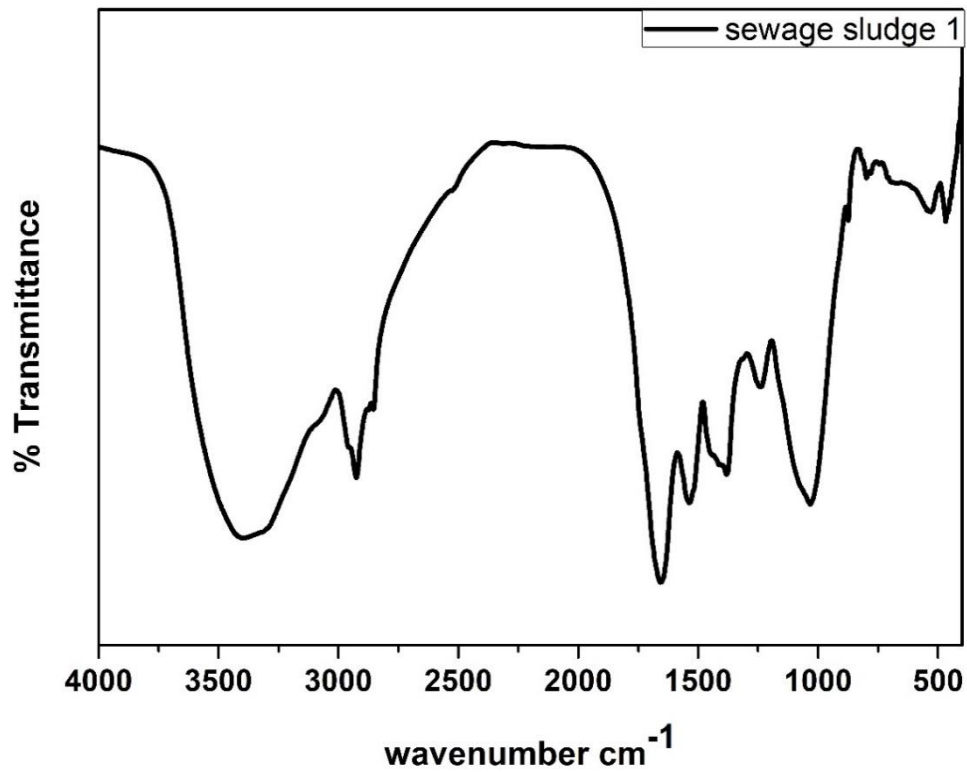
Figure 19: **FTIR of sewage sludge sample obtained from municipal waste water treatment plant**

4.1.4 TGA of Sewage Sludge

Three mass loss curves at heating rates of 5, 10 and 20°C/min were represented in Figure-20. These curves were divided into three stages. Stage one involved removal of inbound moisture at 25-200°C. Second stage involved the disintegration of decomposable organic matter for example proteinases, carboxylic acids, cellulosic compounds and the breakdown of non-convertible carbon-based substance like aromatics, saturated aliphatic, and nitriles at 200-600°C. Second range was the focal part of thermal degradation of sewage sludge because main disintegration occurs in this range. So, this range was further alienated into two ranges one is 200-400°C and other is 400-600°C. Third range was involved the disintegration of inorganic matters like calcium carbonate at

above 600°C. Lopez et al. explained the TGA curve of sewage sludge sample and told that thermal degradation of biomass or other waste materials occur at 700°C and 400°C [35].
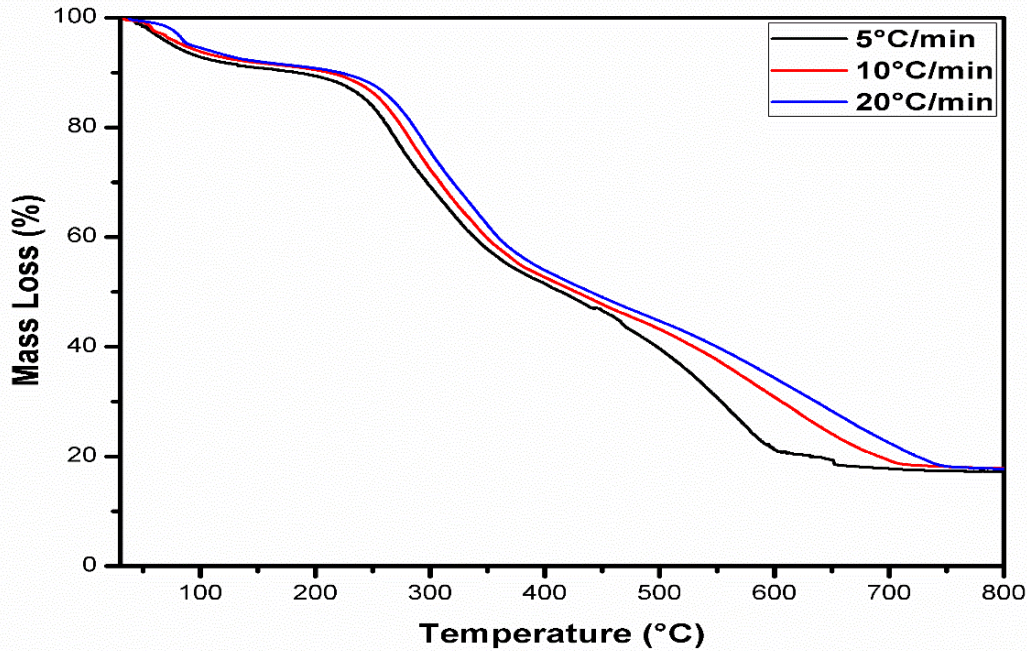
Figure 20: **TGA of Sewage Sludge**

4.2 Gasification Testing

After collection of sample in gas bag as a result of gasification, the testing of gas was performed using GC TCD. These results are taken at different temperature ranges 700 to 850°C and different Equivalence ratio 0.2 to 0.4. The effect on product gas LHV and Cold gas efficiency was also checked using both these parameters. Finally, the optimum condition of Temperature and ER ratio was found at which cold gas efficiency is maximum. All of the results can easily be explained by the reaction in gasification process. Table-7 shows the main reaction involved during gasification process

Table 7: **Main reactions involved during sludge gasification [36][37][38][39]**

Reaction	Oxidation	Enthalpy (MJ/kmol)	Type
R-1	$C + \frac{1}{2}O_2 \rightarrow CO$	-111	Partial Oxidation of Carbon

R-2	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-283	Oxidation of CO
R-3	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	-242	Oxidation of H
R-4	$CnHm + n/2O_2 \leftrightarrow nCO + m/2H_2$	Exothermic	Partial Oxidation of CnHm
Reaction	**Gasification Reaction involving Steam**	**Enthalpy (MJ/kmol)**	**Type**
R-5	$C + H_2O \leftrightarrow CO + H_2$	+131	Water-gas reaction
R-6	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41	Water-gas shift reaction
R-7	$CnHm + nH_2O \leftrightarrow nCO + (n+m/2)H_2$	Endothermic	Steam reforming reaction
Reaction	**Gasification Reaction involving hydrogen**	**Enthalpy (MJ/kmol)**	**Type**
R-8	$C + 2H_2 \leftrightarrow CH_4$	-75	Hydro-gasification
R-9	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	-227	Methanation
Reaction	**Gasification Reaction involving Carbon dioxide**	**Enthalpy (MJ/kmol)**	**Type**
R-10	$C + CO_2 \leftrightarrow 2CO$	+172	Boudouard reaction
R-11	$C_nH_m + nCO_2 \leftrightarrow 2nCO + m/2H_2$	Endothermic	Dry Reforming
Reaction	**Decomposition Reactions of Tar and Hydrocarbons**	**Enthalpy (MJ/kmol)**	**Type**
R-12	$Tar \rightarrow xC_nH_m + yH_2$	Endothermic	De-hydrogenation
R-13	$C_nH_m + \rightarrow nC + m/2H_2$	Endothermic	Carbonization

4.2.1 Effect of Temperature on gas composition (%v/v)

Biomass gasification is a complex thermochemical conversion which is governs by several reactions in table-7. It is evident in Figure-21 that temperature effects the composition of product gas in significant manner.
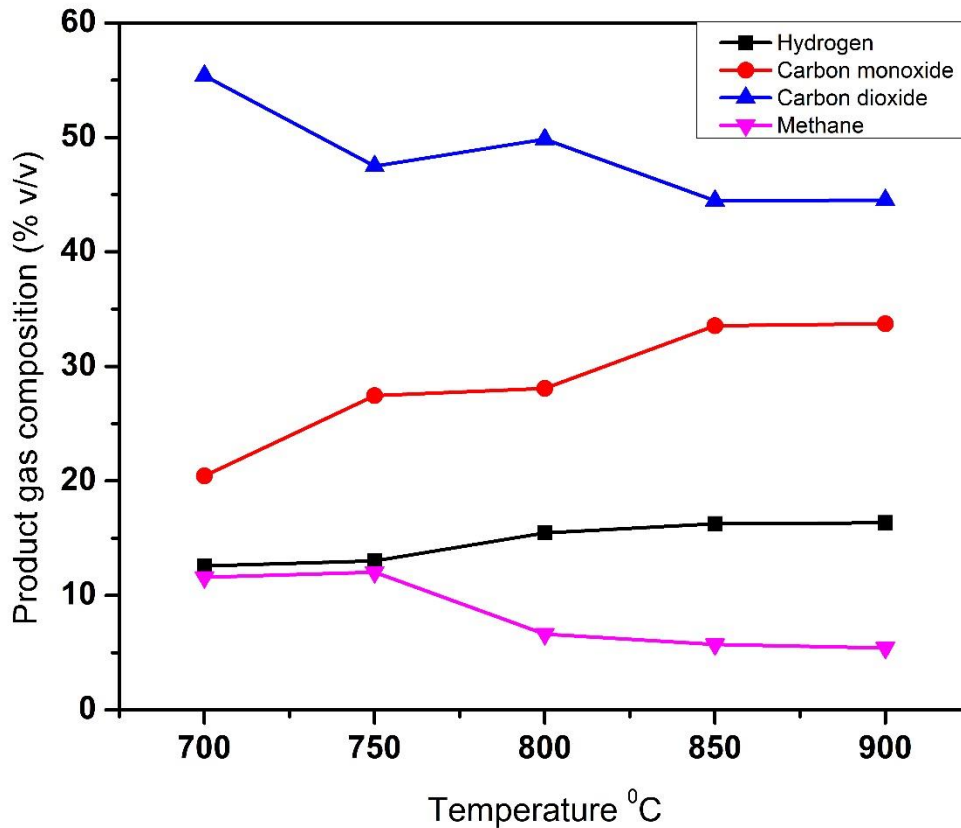
Figure 21: **Effect of temperature on product gas**

By increase in temperature the CO and H2 content increases in the product gas as shown in Figure-21. Same kind of trend also reported by Narvez et al. and Jun Dong et al [40]. This behavior can easily be explained by Le- Chatliers Principle which states that if a pressure is exerted to a reaction process, the process will act in such a way to nullify the effect of that pressure [41]. A high temperature promotes the primary decomposition of char into tar and gas. This primary decomposition of char turned into secondary cracking at elevated temperature.

Therefore increase in hydrogen content is mainly due to following reactions as presented in table7

  a) Water gas reaction (R-5)
  b) Steam Reforming reaction (R-7)
  c) Dry reforming reaction (R-11)

The above reactions are endothermic in nature, according to Le-Chatliers principle, the equilibrium will shift in forward direction for more hydrogen production when temperature increases.

Increase in temperature also increases CO content. This trend is due to following main reactions

  a) Boudouard reaction (R-10)
  b) Water-gas shift reaction (R-6)

Boudouard reaction is endothermic in nature so increasing temperature converts Char into Carbon monoxide. Water-gas shift reaction is exothermic, therefore increasing temperature causes reaction to move in backward direction to produce CO.

An increase or decrease in concentration of CO_2 depends on following reactions.

  a) Cracking of tar (R-12)
  b) Water-gas shift reaction (R-6)

Increasing temperature causes secondary cracking of Tar contents which results in production of Hydrocarbons. These hydrocarbons then react with CO_2 in dry reforming reaction to produce more CO and H_2.Kumari et al. presented same trend in his research work.[42] A high temperature also accelerate reverse water gas shift reaction (RSWG) which results to produce CO and decreases the concentration of CO_2.

Methane contents also shows decreasing trend on increasing temperature. It can easily be understood by following reactions

  a) Hydrogasification (R-8)
  b) Methanation (R-9)

These both reactions are exothermic in nature so increasing temperature make the equilibrium to shift in reverse direction and hence decreases the concentration of CH_4. The same kind of decreasing methane content with increase of temperature also presented by Luo et al.[43]

Table-8 presented the result obtained at temperature ranges from 700-900°C

Table 8; **Temperature dependency on product gas composition (%v/v)**

Temperature ^{O}C	Air/fuel ER	%H$_2$	%CO	%CO$_2$	%CH$_4$
700	0.35	12.573	20.432	55.402	11.591
750	0.35	13.019	27.445	47.501	12.033
800	0.35	15.457	28.075	49.842	6.624
850	0.35	16.259	33.554	44.473	5.712
900	0.35	16.337	33.728	44.532	5.401

Table-9 showing syngas composition as a function of temperature. It shows that syngas composition rises with increase in temperature which is according to reaction mechanism as explained earlier.The composition of syngas becomes constant at 850°C which is selected as optimum temperature for this process. It is shown in Figure-22

Table 9: **Temperature dependency on syngas composition (%v/v)**

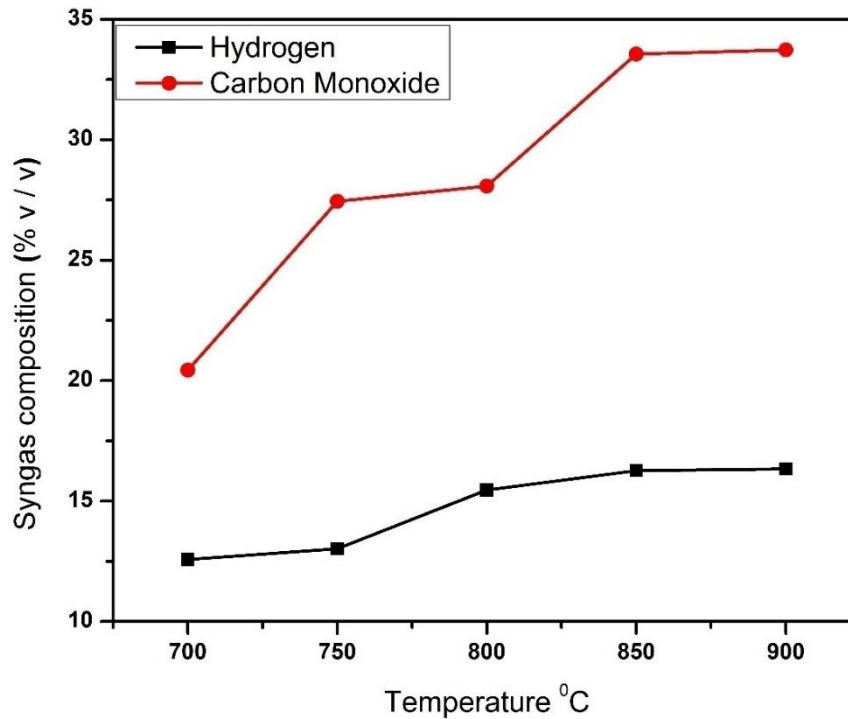| Temperature ^{O}C	Air/fuel ER	%H$_2$	%CO	%Total
700	0.35	12.573	20.432	33.005
750	0.35	13.019	27.445	40.464
800	0.35	15.457	28.075	43.532
850	0.35	16.259	33.554	49.813
900	0.35	16.337	33.728	50.065

Figure 22: **Effect of temperature on syngas composition (%v/v)**

4.2.2 Effect of Equivalence ratio on gas composition

ER defines the quantity of air fed per unit mass off fuel to theoretical amount of air needed for complete combustion [44]. The optimal ER is the one which results in incomplete combustion to produce combustible gases like syngas rather than CO_2 which is result of complete combustion. In this study various experiments have performed at different air ratio varying from 0.2 to 0.4 at 850^0C as shown in figure-23

Results reveals that higher ER ratio increases product gas volume. The main reason lies in mechanism of gasification reaction as shown in table-7

Actually gasification reactions can be divided into two main categories:

a) Primary decomposition of Sewage sludge into gas char and tar
b) Reactions occurred in reducing conditions including reactions of O_2, CO_2, H_2 with hydrocarbon gases.

The partial oxidation reaction get strength at high ER ratio which is presented in table-7 as (R1-R4). This results in decreasing char and tar while increasing syngas yield.

The
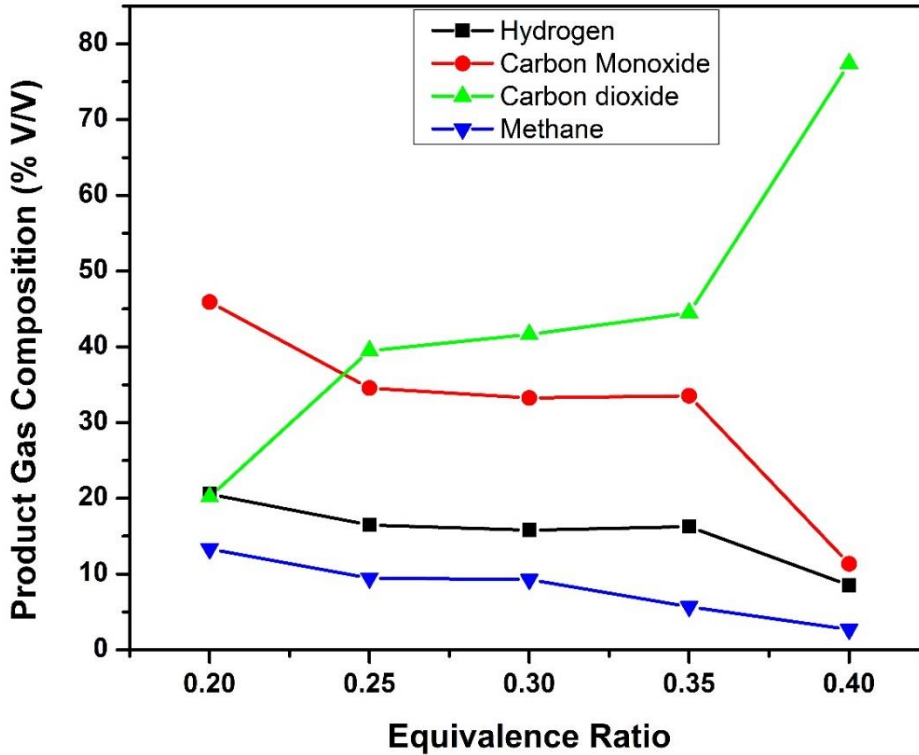
Figure 23: **Effect of ER on product gas**

effect of ER on syngas is shown in Figure-23. Results reveals that at low ER the concentration of syngas increases which is justified by Carbon Partial Oxidation reaction (R1) and Water gas reaction (R5) but as ER exceeds from 0.35the oxidation reaction dominates and the composition of syngas decreases results in low LHV of product gas. The results are also mentioned in table-10. The concentration of CO_2 goes on increasing with increasing ER.Narvaez et al.[45] and Dong et al reported same trend in their work.

Table 10: **Effect of Equivalence ratio on product gas composition (%v/v)**

Temperature ^{o}C	Air/fuel ER	%H_2	%CO	%CO_2	%CH_4
850	0.20	20.562	45.910	20.206	13.320
850	0.25	16.481	34.555	39.484	9.479
850	0.30	15.807	33.264	41.645	9.283
850	0.35	16.259	33.554	44.473	5.712
850	0.40	8.533	11.360	77.410	2.694

4.2.3 Effect of Temperature on gas Lower heating value

The effect of temperature on LHV of gas is shown in figure-24. According to results of gasification process, an increase in temperature kept on increasing syngas yield.
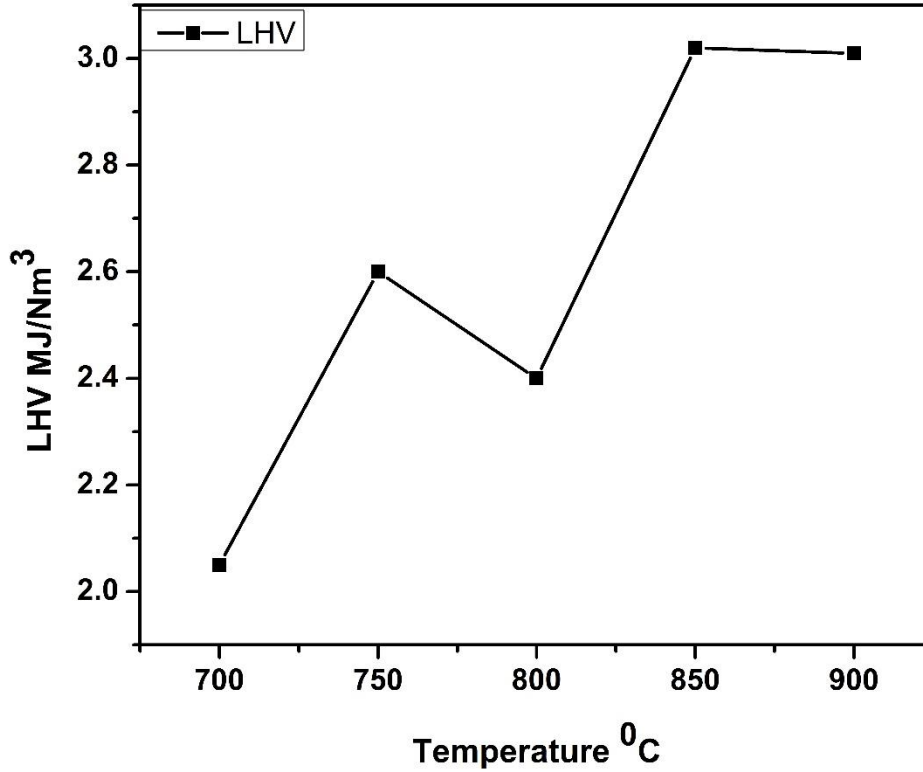
Figure 24: **Effect of Temperature on product gas LHV**

The increasing trend follows up to 850^0C after that no further variation due to temperature was recorded. This is due to complete secondary cracking of tar into syngas. Increasing syngas composition means that LHV of combustible gases increase with increasing temperature.

The equation used to calculate LHV is given below:

LHV gas = (30CO + 25.7H$_2$ + 85.4 CH$_4$) * 0.0042 [46]

Werle et al. and Dong et al. also used same equation to calculate LHV of product gases. [47]

Results are also shown in table-11

Table 11: **Effect of temperature on product gas LHV**

Temperature °C	LHV MJ/Nm³
700	2.05
750	2.60
800	2.40
850	3.02
900	3.01

4.2.4 Effect of ER on gas Lower heating value

Figure-25depicts the LHV of product gas as a function of ER indicating that an increase in ER decreases gas LHV not only because of oxidation of syngas and other combustible gas but dilution effect of N_2 that comes from air. The experiment is conducted at 850^0C which is optimum temperature for this process.

Figure 25: **Effect of ER on product gas LHV**
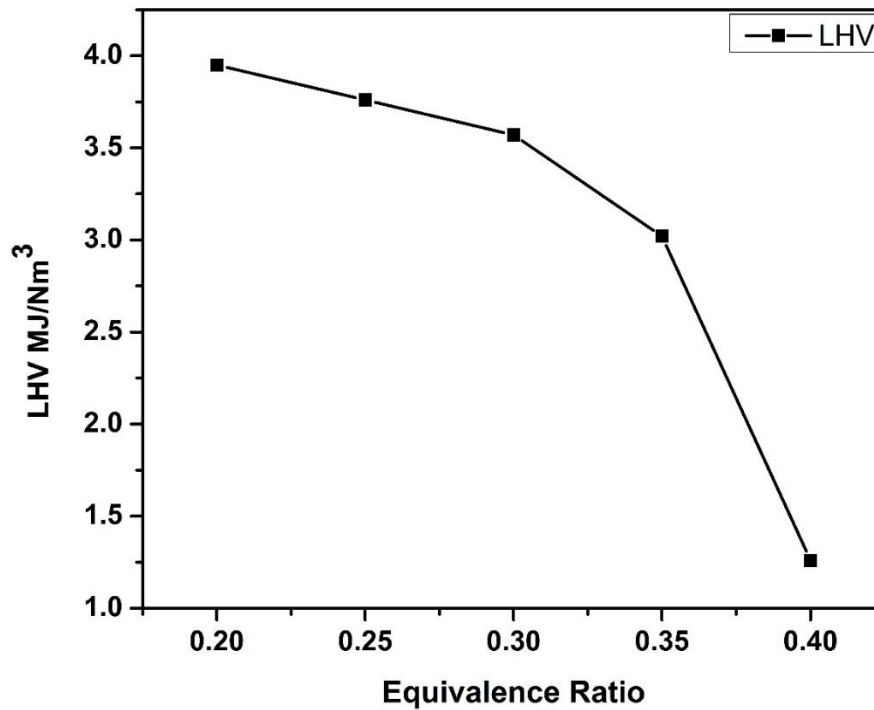
This study demonstrated that ER value should not exceed from 0.35. Niu et al. also observed the optimum value for MSW which should not be more than 0.35 [48]. The results are also presented in table-12.

Table 12: **Effect of ER on product gas LHV**

Equivalence Ratio	LHV MJ/Nm^3
0.20	3.95
0.25	3.76
0.30	3.57
0.35	3.02
0.40	1.26

4.2.5 Effect of temperature on cold gas efficiency

The performance of gasifier is totally dependent on both the quality and the quantity of product gas. The efficiency of gasifier is calculated in terms of cold gas efficiency (CGE).The CGE define as potential of energy output to energy input. [17]

The formula used to calculate cold gas efficiency is given in equation 4.1 [49][46][50]

$$\mathrm{CGE} = \frac{Qg * \mathrm{LHVg}}{Mf * LHVf} \quad (4.1)$$

Where

Qg   = Volumetric flow rate of product gas

LHVg = Lower heating value of gas

Mf   = Mass flow of biomass
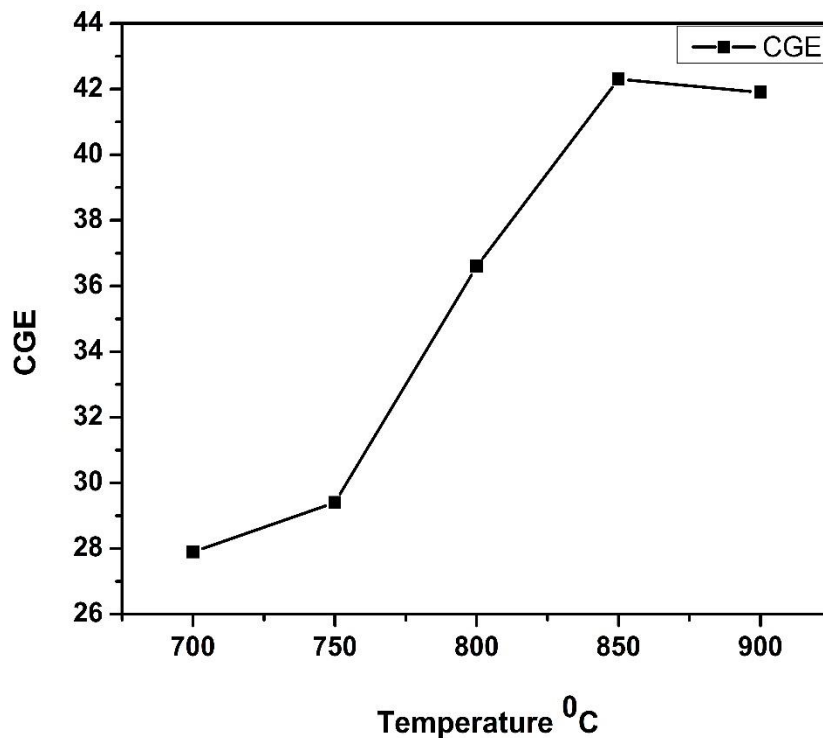
LHV_f = lower heating value of biomass

Figure 26: **Effect of Temperature on CGE**

The Temperature has a direct effect on efficiency of gasifier. Results indicated that rise in temperature causes secondary cracking of tar and char which increases the production of syngas and hence increases both LHV of gas and cold gas efficiency of a gasifier. Ravikiran et al. shows same kind of trend in his research work [56]. Figure-26 shows that the efficiency becomes constant at 900^0C which indicates complete degradation of reactants into products. Highest CGE is found at 850^0C. For each experiment the ER value is kept constant at 0.35. The results are also shown in given table-13

Table 13: **Effect of temperature on CGE**

Temperature ^{0}C	CGE (%)
700	27.9
750	29.4
800	36.6
850	42.3
900	41.9

4.2.6 Effect of ER on cold gas efficiency

Air to fuel ratio is another important parameter which effects the efficiency of gasifier. The Figure-27 shows that increasing the ER ratio increases the CGE of gasifier, this is due the fact that adding more air promotes oxidation reaction and increases the syngas volumetric flow rate.
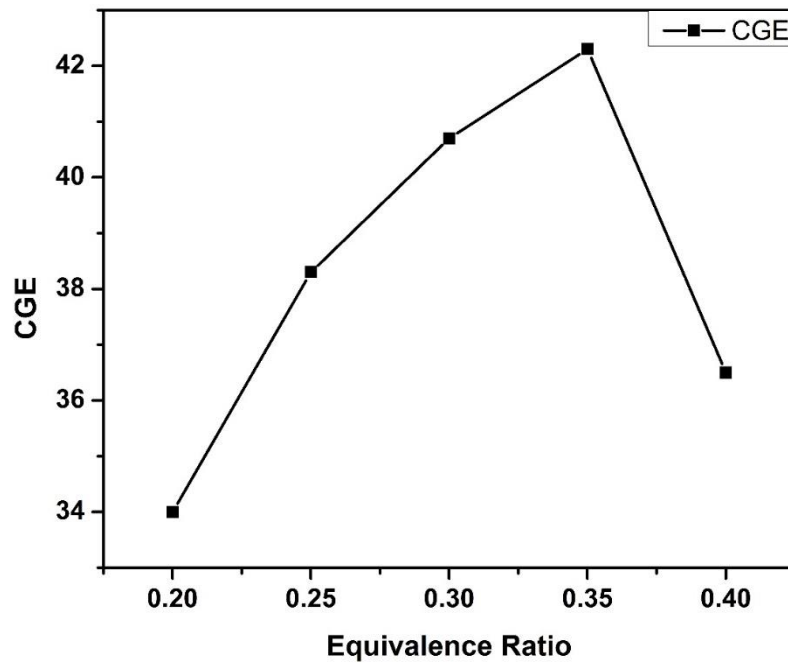
Figure 27: **Effect of ER on CGE**

It can be seen that this increasing trend goes on increasing until ER of 0.35 after that complete combustion results to decrease LHV of gas which in turn decreases the CGE of gasifier. The temperature in each test was fixed to 850^0C. The results are also given in table-14

Table 14: **Effect of ER on CGE**

Equivalence Ratio	CGE (%)
0.20	34
0.25	38.3
0.30	40.7
0.35	42.3
0.40	36.5

Conclusion and Future Recommendation

Conclusions

Gasification of SS was carried out in bubbling fluidized bed gasifier. In each experiment sewage sludge is used in dried and powdered form. The sewage sludge contains high percentage of volatile matter 43.5%, ash contents 43.2%, Carbon 41.4% and Oxygen 45.1%. The calculated low heating value of sewage sludge sample was 15.6MJ/kg.

The high volatile contents and heating value makes sewage sludge a suitable raw material for thermal decomposition for producing combustible fuel gas. FTIR analysis of sewage sludge indicated the presence of amides, aldehydes, Nitriles, aromatic derivatives and carboxylic groups.

The Effect of ER and Temperature on syngas has been studied. The results reveal that both ER and Temperature are dominant parameter that is responsible for distribution of products and characteristics. A rise in temperature accelerated decomposition process and resulted in enhanced H_2 and CO composition. The optimum temperature was found to be 850^0C at which maximum secondary cracking occurred to produce syngas. The cold gas efficiency was also highest at this temperature which was 42.3 at ER of 0.35

The increase in ER boost up oxidation reaction hence increases the product gas yield. Results showed that syngas LHV increases at ER up to 0.35 after that process converted from gasification to combustion and resulted in decreased LHV.

The LHV of gas also effected by both temperature and ER. A high temperature increases the product gas LHV due to enhanced syngas content. The oxidation reaction was also increased with increase in ER value.

A high-quality syngas H_2 16.259% and CO 33.554% with gas LHV $3.02MJ/m^3$ at 850^0C and ER 0.35 with CGE of 42.3 was produced. Comparatively with the results that is published on sewage sludge gasification these values are outstanding and indicated that gasification is better option for valorization of Sewage Sludge.

Future recommendations

By viewing our results, the following suggestions are recommended for gasification process in future.

- Use of alternative gasifying medium other than air such as pure oxygen, steam and Carbon dioxide
- Effect of bed height and catalyst on gasification process.
- Use of alternative fuel source such as bagasse, wood, coal, pine needles.
- Co-gasification of sewage sludge with other fuel source

References

[1].   "BP Statistical Review of World Energy," 2019.

[2].   "When will fossil fuels run out?," 2018.

[3].   "World Energy Outlook 1998."

[4].   http://biofuel.org.uk/what-is-syngas.html

[5].   https://aavos.eu/glossary/syngas-synthesis-gas/

[6].   http://www.airtechnic.cz/biomass-gasification-power-plants/

[7].   http://www.eqtec.es/en/business-areas/waste-gasification/syngas-applications

[8].   Williams, P.T. (2005). Waste treatment and disposal. UK, John Wiley & Sons

[9].   Horan NJ. Biological wastewater treatment systems: theory and operation, series. John Wiley and Sons; 1996.

[10].   Sewage sludge production and disposal - Eurostat." [Online]. Available http://ec.europa.eu/eurostat/web/products-datasets/product?code=env_ww_spd.[Accessed: 12-Dec-2017].

[11].   M. Atienza-Martínez, J. F. Mastral, J. Ábrego, J. Ceamanos, and G. Gea, "Sewage Sludge Torrefaction in an Auger Reactor," *Energy & Fuels*, vol. 29, no. 1, pp. 160–170, Jan. 2015.

[12].   C. He, K. Wang, Y. Yang, and J.-Y. Wang, "Utilization of Sewage-Sludge-Derived Hydrochars toward Efficient Cocombustion with Different-Rank Coals: Effects of Subcritical Water Conversion and Blending Scenarios," *Energy & Fuels*, vol. 28, no. 9, pp. 6140–6150, Sep. 2014.

[13].   D. Fytili and A. Zabaniotou, "Utilization of sewage sludge in EU application of old and new methods—A review," *Renew. Sustain. Energy Rev.*, vol. 12, no. 1, pp. 116–140, Jan. 2008.

[14].   A. Raheem, M. Y. Hassan, and R. Shakoor, "Bioenergy from anaerobic digestion in Pakistan:Potential, development and prospects," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 264–275 Jun. 2016

[15]. Ferrasse, J.-H.; Seyssiecq, I.; Roche, N. Thermal gasification: A feasible solution for sewage sludge valorisation? Chemical Engineering & Technology 2003, 26(9), 941–945.

[16]. Gasification, Producer Gas and Syngas Sammy Sadaka

[17]. Biomass Gasification,Pyrolysis, and Torrefaction Practical Design and Theory Second Edition Prabir Basu

[18]. Effect of Operating Parameters and Moisture Content on Municipal Solid Waste Pyrolysis and Gasification Jun Dong, Yong Chi

[19]. Gaseous fuels production from dried sewage sludge via air gasification Sebastian Werle1 and Mariusz Dudziak

[20]. Gasification of wastes in a pilot fluidized bed gasifier Manuel Campoy ∗, Alberto Gómez-Barea

[21]. An Experimental Investigation of Sewage Sludge Gasification in a Fluidized Bed Reactor L. F. Calvo

[22]. Influence of gas residence time and air ratio on the air gasification of dried sewage sludge in a bubbling fluidised bed Joan J. Manya

[21]. An Experimental Investigation of Sewage Sludge Gasification in a Fluidized Bed Reactor L. F. Calvo

[23]. K. Murata, Y. Liu, M. Inaba, and I. Takahara, "Catalytic fast pyrolysis of jatropha wastes," J. Anal. Appl. Pyrolysis, vol. 94, pp. 75–82, Mar. 2012.

[24]. D. R. Nhuchhen and P. Abdul Salam, "Estimation of higher heating value of biomass from proximate analysis: A new approach," *Fuel*, vol. 99, pp. 55–63, Sep. 2012.

[25]. H. Günzler and H.-U. Gremlich, *IR spectroscopy : an introduction*. Wiley-VCH, 2002.

[26]. P. Inc, "Thermogravimetric Analysis (TGA) The Thermogravimetric Instrument Family."

[27]. Towards sewage sludge based biofuels via thermochemical conversion – A review P. Manara

[28]. Co-pyrolysis characteristics of municipal sewage sludge and hazelnut shell by TG-DTG-MS and residue analysis," *Waste Manag.*, vol. 62, pp. 91–100, Apr. 2017

[29]. Gaseous fuels production from dried sewage sludge via air gasification Sebastian Werle1 and Mariusz Dudziak

[30]. A. Demirbaş, "Calculation of higher heating values of biomass fuels," *Fuel*, vol. 76, no. 5, pp. 431–434, Apr. 1997.

[31].   J.-P. Cao *et al.*, "Nitrogen transformations during fast pyrolysis of sewage sludge," *Fuel*, vol. 104, pp. 1–6, Feb. 2013.

[32].   W. Zuo, B. Jin, Y. Huang, and Y. Sun, "Characterization of top phase oil obtained from sewage sludge and poplar sawdust," *Environ. Sci. Pollut. Res.*, vol. 21, no. 16, pp. 9717–   9726, Aug. 2014.

[33].   M. Jeguirim and G. Trouvé, "Pyrolysis characteristics and kinetics of Arundo donax using thermogravimetric analysis," *Bioresour. Technol.*, vol. 100, no. 17, pp. 4026–4031, Sep.   2009.

[34].   D. Vamvuka, E. Kakaras, E. Kastanaki, and P. Grammelis, "Pyrolysis characteristics and kinetics of biomass residuals mixtures with lignite☆," *Fuel*, vol. 82, no. 15–17, pp. 1949–   1960, Oct. 2003.

[35].   M. A. Lopez-Velazquez, V. Santes, J. Balmaseda, and E. Torres-92 Garcia, "Pyrolysis of orange waste: A thermo-kinetic study," *J. Anal. Appl. Pyrolysis*, vol. 99, pp. 170–177, Jan.   2013.

[36].   Effect of Operating Parameters and Moisture Content on Municipal Solid Waste Pyrolysis and Gasification, Jun Dong, Yong Chi,

[37].   Steam gasification of pine needles using CaO as catalyst and sorbent for hydrogen production with CO_2 capture

[38].   Experimental study on non-woody biomass gasification in a downdraft gasifier Chao Gai

[39].   Experimental study on catalytic steam gasification of municipal solid waste for bioenergy production in a combined fixed bed reactor Li etal.

[40].   Narváez, I.; Orío, A.; Aznar, M. P.; Corella, J. Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Ind. Eng.Chem. Res. 1996, 35 (7), 2110−2120.

[41].   Equillibria Chem.libertexts.org

[42].   Steam gasification of pine needles using CaO as catalyst and sorbent for hydrogen production with CO_2 capture Kumari, Priti; IIT Roorkee, chemical engineering Mohanty, Bikash; IIT Roorkee

[43].   Syngas production by catalytic steam gasification of municipal solid waste in fixed-bed reactor Siyi Luo*, Yangmin Zhou

[44].   Gasification of a Dried Sewage Sludge in a Laboratory Scale Fixed Bed Reactor Sebastian Werle

[45]. Narváez, I.; Orío, A.; Aznar, M. P.; Corella, J. Biomass gasification with air in an atmospheric Bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Ind. Eng. Chem. Res. 1996, 35 (7), 2110−2120

[46]. Gasification of Tibetan herb residue: Thermogravimetric analysis and experimental study

[47]. Gasification of a Dried Sewage Sludge in a Laboratory Scale Fixed Bed Reactor Sebastian Werle

[48]. Niu, M.; Huang, Y.; Jin, B.; Wang, X. Simulation of syngas production from municipal solid waste gasification in a bubbling fluidized bed using Aspen Plus. Ind. Eng. Chem. Res. 2013, 52 (42),14768−14775

[17]. Biomass Gasification,Pyrolysis, and Torrefaction Practical Design and Theory   Second Edition Prabir Basu

[49]. Chemical Engineering and Reactor Design of a Fluidised Bed Gasifier.By Abbas Abdulkareem Mahmood AL-Farraji

[46]. Gasification of Tibetan herb residue: Thermo gravimetric analysis and experimental Study

[50]. Experimental study of gasification characteristic of biomass with CO_2/Air in entrained flow gasifier Haimio YU