GASIFICATION CHARACTERISTICS OF SUGARCANE BAGASSE

University of Fort Hare
Together in Excellence

ANTHONY IKE ANUKAM

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Supervisors: Professor E. L. Meyer, Dr S. Mamphweli and Dr O. Okoh

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DECLARATION

By submitting this dissertation electronically or otherwise, I declare that the entirety of the work contained therein is my own, original work, that I am the proud owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: January 10, 2013

Signature: ……..

Signed on this……..day of……..year……...

DEDICATION

To Almighty God, my father, mother and siblings

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SUMMARY

Sugarcane is a major crop in many countries. It is the most abundant lignocellulosic material in tropical countries such as South Africa. It is one of the plants with the highest bioconversion efficiency. The sugarcane crop is able to efficiently fix solar energy, yielding some 55 tons of dry matter per hectare of land annually. After harvest, the crop produces sugar juice and bagasse. Sugarcane bagasse is a residue that results from the crushing of sugarcane in the sugar industry. It is a renewable feedstock that can be used for power generation and manufacturing cellulosic ethanol. As biomass, sugarcane bagasse holds promise as a fuel source since it can produce more than enough electricity and heat energy to supply the needs of a common sugar factory. However, in the sugarcane industry the bagasse is currently burnt inefficiently in boilers that provide the heating for the industry. This project seeks to investigate the possibility of gasifying sugarcane bagasse as an efficient conversion technology. The investigation is necessary because fuel properties govern the gasifier design and ultimately, the gasification efficiency. Proximate and ultimate analysis of sugarcane bagasse was conducted after which the results were used to conduct a computer simulation of the mass and energy balance during gasification. The kinetic investigation undertaken through the TGA and DTG analyses revealed the activation energy and pre – exponential factor which were obtained by the model – free Kissinger method of kinetic analysis and were found to be 181.51 kJ/mol and 3.1×10^3/min respectively. The heating value of sugarcane bagasse was also measured and found to be 17.8 MJ/kg, which was used in the calculation of the conversion efficiency of the gasification process. Fuel properties, including moisture content and gasifier operating parameters were varied in order to determine optimum

gasifier operating conditions that results in maximum conversion efficiency. The highest conversion efficiency was achieved at low moisture content after computer simulation of the gasification process. Moisture content also affected the volume of CO and H_2 as the former decreases with increasing moisture content while the latter increases with increasing moisture content, accelerating the water – gas reaction. Scanning electron microscope fitted to an Energy dispersive X – ray spectroscopy was also used in order to view the shape and size distribution as well as determine the elemental composition of sugarcane bagasse. The results obtained established that the fuel properties and gasification conditions affect the conversion efficiency. During computer simulation, it was established that smaller particle size resulted in higher conversion efficiency. The smaller throat diameter also resulted in higher conversion efficiency. The throat angle of 25° also resulted in higher conversion efficiency. The temperature of input air was also found to be one of the major determining factors in terms of conversion efficiency. The dissertation presents the proximate and ultimate analysis results as well as the kinetic analysis results. The SEM/EDX analysis as well as the computer simulation results of the gasification process is also presented.

The major contribution of this project was on the investigation of the gasification characteristics of sugarcane bagasse and the utilization of these in the design of a laboratory scale sugarcane bagasse gasifier with enhanced conversion efficiency through computer simulation.

Keywords: Sugarcane Bagasse, gasification, proximate analysis, ultimate analysis, mass and energy balance, computer simulation.

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LIST OF ABBREVIATIONS

AC – Ash content

BIGCC – Biomass Integrated Gasification Combined Cycle system

BBBEE – Broad – based Black Economic Empowerment

DTG – Derivative Thermo Gravimetry

EPA – Environmental Protection Agency

FAO – Food and Agriculture Organization

GCEP – Global Climate and Energy Project

HCN – Hydrogen Cyanide

HPLC – High Performance Liquid Chromatography

MC – Moisture content

NCBP – Natal Cane By-Products

NETL – National Energy Technology Laboratory

SACU – South African Customs Union

SADME – South Africa Department of Minerals and Energy

SASA – South African Sugar Association

SASI – South African Sugar Industry

SACGA – South African Cane Growers Association

SCTD – Schumacher Centre for Technology and Development

SERI – Solar Energy Research Institute

SMRI – Sugar Milling Research Institute

SB – Sugarcane Bagasse

TA – Throat Angle

TCD – Thermal Conductivity Detector

TD – Throat Diameter

TGA – Thermo Gravimetric Analysis

UNECA – United Nations Economic Commission for Africa

VMC – Volatile Matter Content

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The development of sustainable renewable energy technologies for their use in current and new power plants is of utmost importance now than ever before due to several reasons. Some of these reasons include energy security and availability, independency from foreign crude oil supply and reduction of greenhouse gas emissions to provide cleaner environment for better health, plant and animal life. These reasons are precepts for the development of alternative and sustainable energy technologies.

Gasification of sugarcane bagasse provides part of the solution towards sustainable renewable energy sources. Gasification is considered the most suitable option because it offers higher efficiencies compared to other thermochemical methods of conversion [Ardila *et al*., 2011]. Sugarcane bagasse gasification has the advantage of syngas production which is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperatures or even in fuel cells. Furthermore, gasification has the flexibility in the sense that using the syngas produced can be transformed to liquid fuels. Among the various agricultural crop residues, sugarcane bagasse is one of the most abundant lignocellulosic material in tropical countries such as South Africa.

Bagasse is a residue produced in large quantities by sugar and alcohol industries. It is the fiber left over after the juice has been squeezed out of sugarcane stalks. Figure 1.1 (a)

shows a sugarcane plantation while (b) shows the bagasse as produced from the sugarcane after extraction of the juice in the sugarcane.

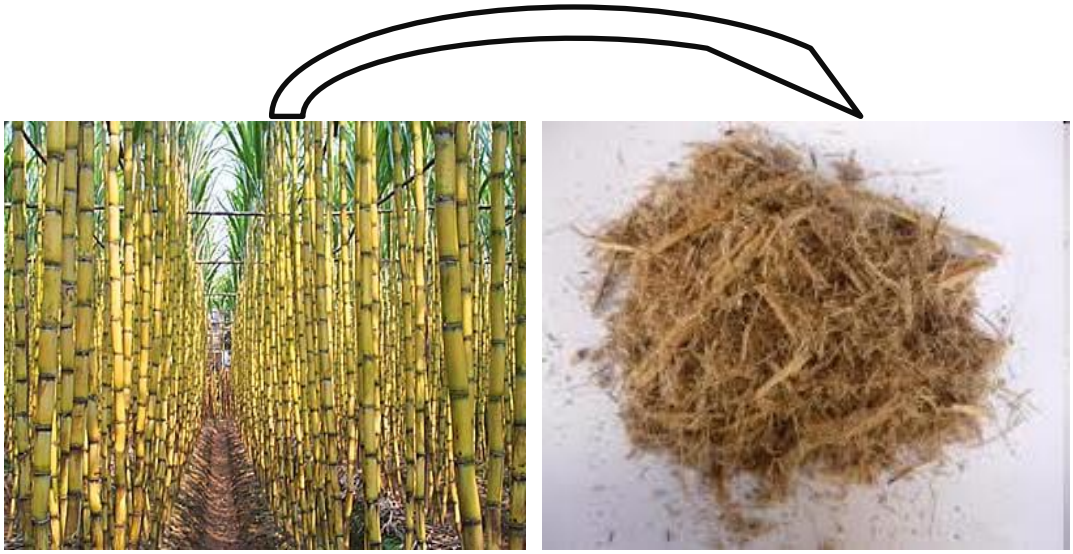

Figure 1.1 (a): Sugarcane Plantation, [www.21food.com]

Figure 1.1 (b): Sugarcane Bagasse [www.trussty – jasmine.blogsopt.com].

Generally, 1 ton of sugarcane generates 280 kg of bagasse and about 54 million dry tons of bagasse is produced annually throughout the world [Samariha and Khakifirooz, 2011]. In South Africa approximately 6 million tons of raw bagasse is produced annually [Johannes, 2010]. Most large and medium sized mills can use up to 75% of this bagasse onsite to generate heat and electricity [Zandersons *et al*., 1999].

This product represents a great morphological heterogeneity. It consists of fiber bundles and other structural elements like vessels, parenchyma, and epithelial cells [Sanjuan *et al*., 2001]. The sugarcane residues can be divided into bagasse and cane trash. Sugarcane

bagasse is the major by – product of the sugar industry and is almost completely used by the sugar factories themselves as fuel for their boilers.

As biomass, bagasse holds promise as a fuel source since it can produce more than enough heat energy to supply the needs of a common sugar mill [Enviro Engineers, 2007]. On average, about 300 000 tons of sugarcane bagasse are generated per annum per sugar mill in South Africa and this amount generates about 124 tons/hr of heat in the form of process steam to the mill and about 56 MWe of electricity (10 MWe to be used by the sugar mill itself and 46 MWe by the rest of the community where the mill is located) [Lewis, 2004]. Sugarcane bagasse is a renewable feedstock that can be used for power generation and manufacturing cellulosic ethanol. It may also be used as fuel in the sugarcane mill or as a source of cellulose for manufacturing animal feeds. Paper is produced from bagasse in several Latin – American countries, in the Middle East, and in all sugar-producing countries that are deficient in forest resources. Bagasse is the essential ingredient for the production of pressed building board, acoustical tile, and other construction materials. Due to its abundance, it can serve as an ideal substrate for microbial processes as well as energy conversion via combustion or gasification for the production of fuels and value – added products [Ahmed *et al*., 2011]. Gasification of sugarcane bagasse produces the same amount of CO_2 as it consumes during its growth rendering it carbon neutral [Mamphweli, 2009]. However, limited data are available for the efficient conversion of bagasse to clean syngas as well as low attention been paid to its gasification characteristics. This research presents the gasification characteristics and properties of sugarcane bagasse.

Sugarcane bagasse can be converted into energy in a variety of ways. Figure 1.2 shows the various methods of converting sugarcane bagasse to useful energy.

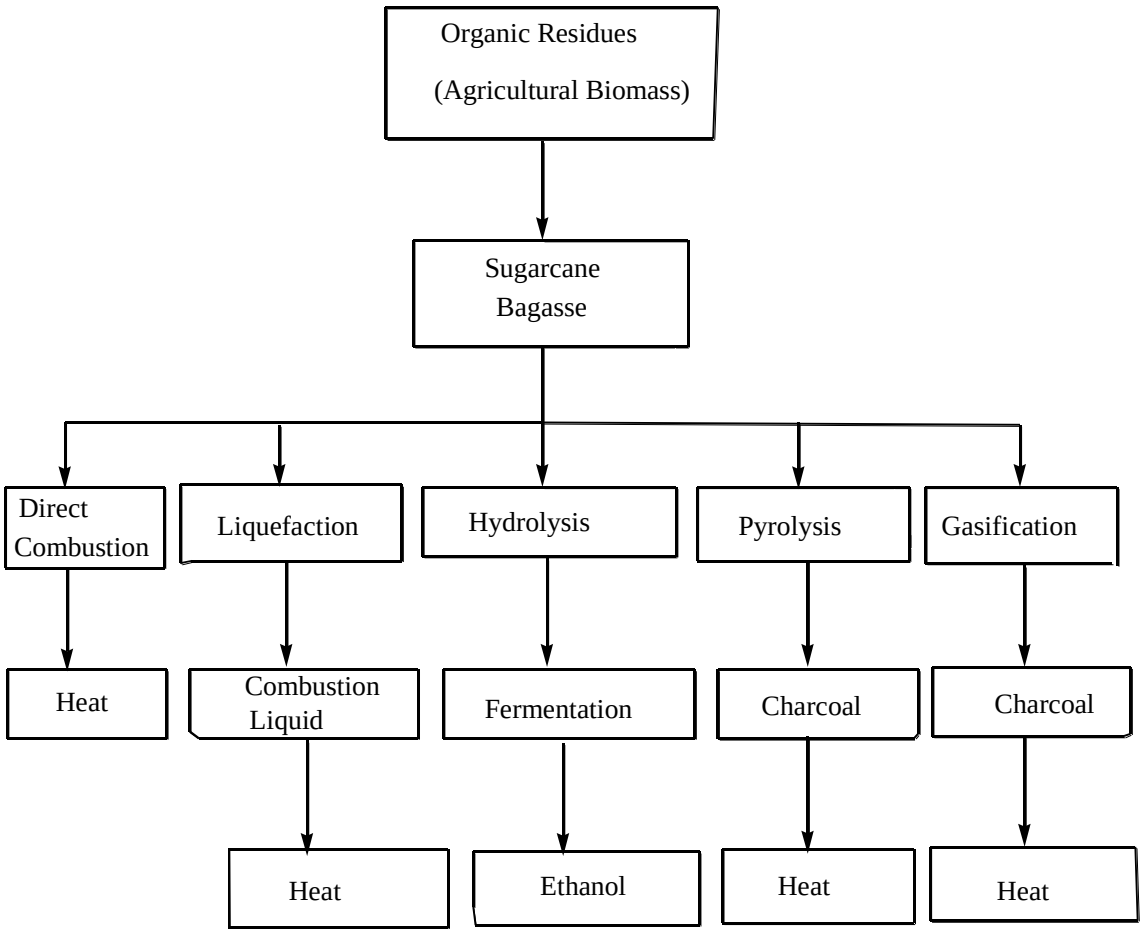

Figure 1.2 Schematic diagram of the processes of energy conversion of sugarcane bagasse. [Silvio *et al*., 2010].

Of the various methods available to convert sugarcane bagasse into useful energy, gasification happens to be the main focus of this research. A detailed explanation of gasification is provided in subsequent chapters of this dissertation.

1.2 PROBLEM STATEMENT

Sugarcane is a major crop in many countries. It is one of the plants with the highest bioconversion efficiency. Sugarcane crop is able to efficiently fix solar energy, yielding some 55 tons of dry matter per hectare of land annually. After harvest, the crop produces sugar juice and bagasse, the fibrous dry matter. This dry matter is a well established biomass feedstock with potential as fuel for energy production.

Since plenty of bagasse is produced per unit of sugarcane crushed, relatively little attention has been paid to its efficient utilization in South Africa. Its utilization as an energy product in the sugar industry is not optimized with respect to current upgrading technologies. Most of the bagasse is burnt inefficiently in furnaces to generate process steam and, in certain instances, to generate electricity. This research therefore sought to establish the gasification characteristics of sugarcane bagasse as an efficient conversion technology in South Africa.

1.3 RESEARCH OBJECTIVES

The main objective of this project was to investigate the gasification characteristics and properties of sugarcane bagasse and use them to simulate the mass and energy balance during gasification. The simulated parameters that results in high conversion efficiency can then be used to come up with a gasifier with enhanced conversion efficiency.

The specific objectives were as follows:

i. To characterize the bagasse in terms of proximate and ultimate analysis as well as kinetic analysis
ii. To conduct computer simulation of the mass and energy balance during gasification of the bagasse including gas production under various gasifier operating conditions and determine the optimum gasifier operating conditions/design that results in maximum conversion efficiency.

1.4 RATIONALE OF THE STUDY

The sugar industries produces surplus amounts of sugarcane bagasse. The burning of sugarcane bagasse in sugar mills for meeting internal energy needs is inefficient and wasteful and there has been significant interest in converting this waste (bagasse) into higher energy density fuel by various means such as combustion, pyrolysis, carbonization and gasification. Furthermore, the sugar industries burn most of the sugarcane bagasse in furnaces for the production of steam. The furnaces in which the sugarcane bagasse are traditionally burnt for steam production have energy efficiency rates of approximately 60 – 65%; whereas it is possible to achieve efficiency rates of nearly 90%, with heat-recovery designs and systems to reduce the final temperature of combustion gases. These traditional energy schemes were designed to obtain precisely the electrical power required by the factory as the steam produced by low-pressure turbo generators passes through the steam generators. The gasification of sugarcane bagasse could result in a more efficient process in a combined heat and electricity system.

1.5 DELINEATION AND LIMITATION

The biomass material that has been chosen for this study is sugarcane bagasse because of its availability in excess of its usage and because an industrial infrastructure for a sugarcane bagasse processing plant could be provided by the sugar mills. Large amounts of bagasse are produced as waste by the sugar industries. However, the major challenge of the sugar industry has been the efficient conversion of this waste into a form of energy. This study seeks to investigate the possibility of gasifying sugarcane bagasse as an efficient conversion technology. Determination of mass and energy balance by computer simulation of the gasification process will also be undertaken as well as the design of an efficient technology for sugarcane bagasse gasification. The actual gasification of the material will not be conducted, instead, the study will rely on the mass and energy balance results obtained using computer simulations. The proximate and ultimate analysis as well as the computer simulation results are presented and discussed in relation to the suitability for gasification using existing literature, thereby negating the need to repeat measurements or experiments that has already been undertaken by other researchers.

1.6 DEFINITION OF TERMS

The following terms should be used and understood as defined in this section unless the context suggests otherwise:

Bagasse is the fibrous matter left over after the extraction of the juice from sugar cane stalks.

Biomass is biological material derived from living organisms; the material is also carbonaceous.

Gasification refers to the thermal conversion of carbonaceous materials into a gaseous energy carrier known as syngas or producer gas in the presence of very little quantities of air.

Gasifier is a reactor in which the gasification process or conversion of carbonaceous materials into syngas or producer gas takes place.

Syngas refers to the mixture of gases resulting from the gasification process.

Computer simulation is a computer program that attempts to simulate an abstract model of a particular system.

1.7 RESEARCH QUESTIONS

i. What are the gasification characteristics of sugarcane bagasse and what impact do these have on the design of an efficient gasifier?

ii. What are the possible mass and energy balances obtained during gasification of sugarcane bagasse under different gasification conditions?

iii. What are the optimum gasifier operating conditions and design parameters that result in maximum conversion efficiency?

1.8 DESSERTATION OUTLINE

This dissertation discusses the gasification characteristics of sugarcane bagasse. It is subdivided into five chapters as follows:

Chapter 1: Introduction

This chapter gives the background of the research. The objectives, motivation/rationale, research questions, as well as delineation and limitations of the work are presented in this chapter. A brief overview of the methodology is also presented in this chapter.

Chapter 2: Literature review

This chapter presents a synthesis of relevant literature. The various sources of information about sugarcane bagasse (SB), current use as well as its characteristics and properties are presented in this chapter. The gasification process and various types of gasifiers are also presented in this chapter. This chapter is meant to gain an understanding of the gasification characteristics and properties as available in literature.

Chapter 3: Research methodology

This chapter presents the various methods employed in data collection and analysis. These methods were carefully chosen to collect relevant data that could assist in answering the research questions and achieve the objectives of the research. The methods are presented in this chapter in detail with justification for the choice of the methods with specific reference to the research objectives.

Chapter 4: Results and discussions

This chapter presents the results obtained using methods presented in chapter 3. The results are presented and discussed with reference to existing literature. The key aspects of the results are highlighted and compared to existing knowledge.

Chapter 5: Summary, Conclusion and Recommendations

This chapter presents the summary of the whole research project. A conclusion is also drawn from the results presented in chapter 4. A summary of the research contributions is also presented in this chapter. The recommendations for further research are also made in this chapter. This basically covers what this project could not cover mainly due to the scope of the research but these aspects are found to be important to warrant an investigation.

Appendix A: Research outputs

Appendix A lists the research outputs associated with this work. These are papers presented at national conferences; papers published in conference proceedings as well as papers submitted for publication in peer – reviewed journals.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

In determining the suitability of biomass materials for gasification a good understanding of its constituent is necessary. The performance of each type of biomass as a fuel in combustion or gasification devices or both is determined by its specific properties as biomass materials vary in their physical, chemical and morphological properties. This chapter will present a review of literature on the structure and chemical composition of sugarcane bagasse, the process of crushing sugarcane and the resultant bagasse, the availability and current use of sugarcane bagasse in South Africa, the biomass gasification process, the gasification of sugarcane bagasse, as well as sugarcane industries in South Africa.

The chemical composition of sugarcane bagasse found in the literature varies widely due to differences in the type of plant and soil where the sugarcane was grown.

2.2 STRUCTURE AND CHEMICAL COMPOSITION OF SUGARCANE BAGASSE

The most important components relating to the conversion of any biomass material are cellulose, hemicellulose, lignin, ash, protein, volatile matter, moisture content and extractables. The proportion of each of the these components is critical in evaluating the suitability of the biomass for gasification [Osita, 2008]. A limited number of studies have been reported for the composition of sugarcane bagasse but no comprehensive

compositional analyses have been reported for South African varieties of sugarcane bagasse [Sugar Milling Research Institute, 2008].

Sugarcane bagasse consists of approximately 50% cellulose and 25% each of hemicellulose and lignin [Ahmed *et al*., 2011]. Chemically, sugarcane bagasse contains about 50% alpha-cellulose, 30% pentosans, and 2.4% ash. Because of its low ash content, sugarcane bagasse offers numerous advantages in comparison to other crop residues such as rice straw and wheat straw, with 17.5% and 11.0% ash contents, respectively. In comparison to other agricultural residues, sugarcane bagasse can also be considered as a rich energy reservoir due to its high yields (about 80 t/ha in comparison to about 1, 2, and 20 t/ha for wheat, other grasses and trees, respectively) and annual regeneration capacity [Pandey *et al*., 2000].

The compositional analysis of sugarcane bagasse is presented in table 2.1.

Table 2.1 Proximate analysis of SB. (% w/w of the dry matter) [Muhammad *et al*., 2011].

Content	**(%) Composition**
Cellulose	40
Lignin	23
Total Sugars	2.94
Reducing sugars	8.05
Ash	0.9
Moisture	7.1

Sugarcane bagasse consists of 40% cellulose and between 23 – 25% hemicellulose and lignin [Muhammad *et al*., 2011, Saha *et al*., 2003, Sun *et al*., 2002 and Martin *et al*., 2002]. The partial composition of sugarcane bagasse is presented in table 2.2.

Table 2.2 The composition of SB. (% w/w of the dry matter) [Pessoa *et al*., 1997]

Component	**(%) Composition**
Total Reducing Sugars	70.9
Xylose	25.2
Glucose	41.0
Fermentable Reducing Sugars	44.6
Non-fermentable Reducing Sugars	26.3
Lignin	23.0
Ash	1.1
Moisture	47.8

The ash content is low, owing perhaps to the influence of different factors on sugarcane cultivation and processing. Table 2.2 also shows that 26.3% of NFRS and 44.6% of FRS are composed of xylose and glucose respectively. The difference could be ascribed to the fact that arabinose, mannose, and oligomers are present in the hemicellulose originating in incomplete molecule hydrolysis. The difference could also be as a result of the presence of compounds like 4-O-methyl-glucuronic acid, aldobiuronic acid and galactose, which were not detected by HPLC used by the authors. Using two different techniques (colorimetric method and HPLC), on the other hand, also interferes with the concentrations of sugar [Pessoa *et al*., 1997; Fox *et al.* 1984; Morjanoff and Gray 1987].

Sugarcane bagasse has very high volatile matter content and low ash content, this makes it suitable for pyrolysis and gasification. Table 2.3 shows the proximate analysis of sugarcane bagasse.

Table 2.3 Proximate analysis of bagasse (wt. %) [Surinder *et al*., 2003].

Component	**(%) Composition**
Moisture (As received)	8.20
Volatile matter (Moisture free basis)	83.10
Ash (Moisture free basis)	4.20
Fixed carbon (Moisture free basis, By difference)	12.70

The ash content and its composition are important factors for biomass use in thermochemical processing due to its catalytic activity [Bridgwater *et al*., 1995, Shafizadeh *et al*., 1982 and Ravinderan *et al*., 1996].

2.2.1 Cellulose

Cellulose is the major component in the rigid cell walls in plants. It is a linear polysaccharide polymer with many glucose monosaccharide units. It may have a degree of polymerization in excess of 10 000 as can be seen from its structure. The acetal linkage is beta which makes it different from starch. The linear structure of the cellulose chain enables the formation of inter- and intramolecular hydrogen bonds. This results in the aggregation of about 36 glucose chains into crystalline fibrils [Ding and Himmel, 2006]. Approximately 50 – 90% of the total cellulose in the biomass is crystalline, depending on the biomass source [Jacobsen and Wyman, 2000]. The combination of the structure and intermolecular hydrogen bonding gives cellulose a resistance against

microbial attack, a high tensile strength and makes it insoluble in most solvents [Sugar Milling Research Institute, 2008]. Figure 2.1 shows the structure of cellulose.

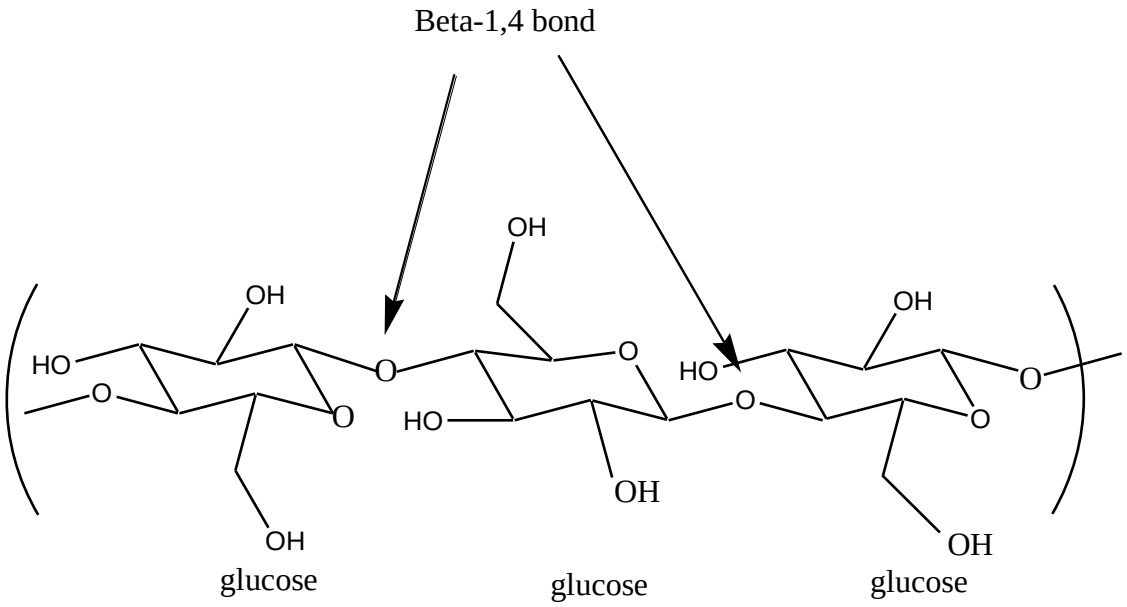

Figure 2.1 Structure of cellulose [SMRI, 2011].

The gasification behaviour of cellulose is important in understanding the gasification of biomass materials. During gasification, the tar and gas yields increases with the growth of cellulose content while the yield of char decreases. The main gas products from cellulose are CO_2 and CO because monosaccharides such as glucose from the cellulose are decomposed to CO_2 and CO through decarboxylation.

2.2.2 Hemicellulose

Hemicellulose is a heterogeneous polysaccharide composed of D-xylose, D-glucose, D-mannose, D-galactose, L-arabinose, D-glucuronic acid and 4-O-methyl-D-glucuronic acid. The specific composition varies among different plants. It has a very low degree of polymerization (typically below 200), often contains side chains and is typically acetylated. Classification is according to the main sugar in the polymer backbone, e.g. xylan (β-1, 4-linked xylose) or mannan (β-1, 4-linked mannose). Bagasse hemicellulose is composed of a backbone of xylose, branched with glucose and arabinose units [Sun *et al*., 2004] as shown in figure 2.2.

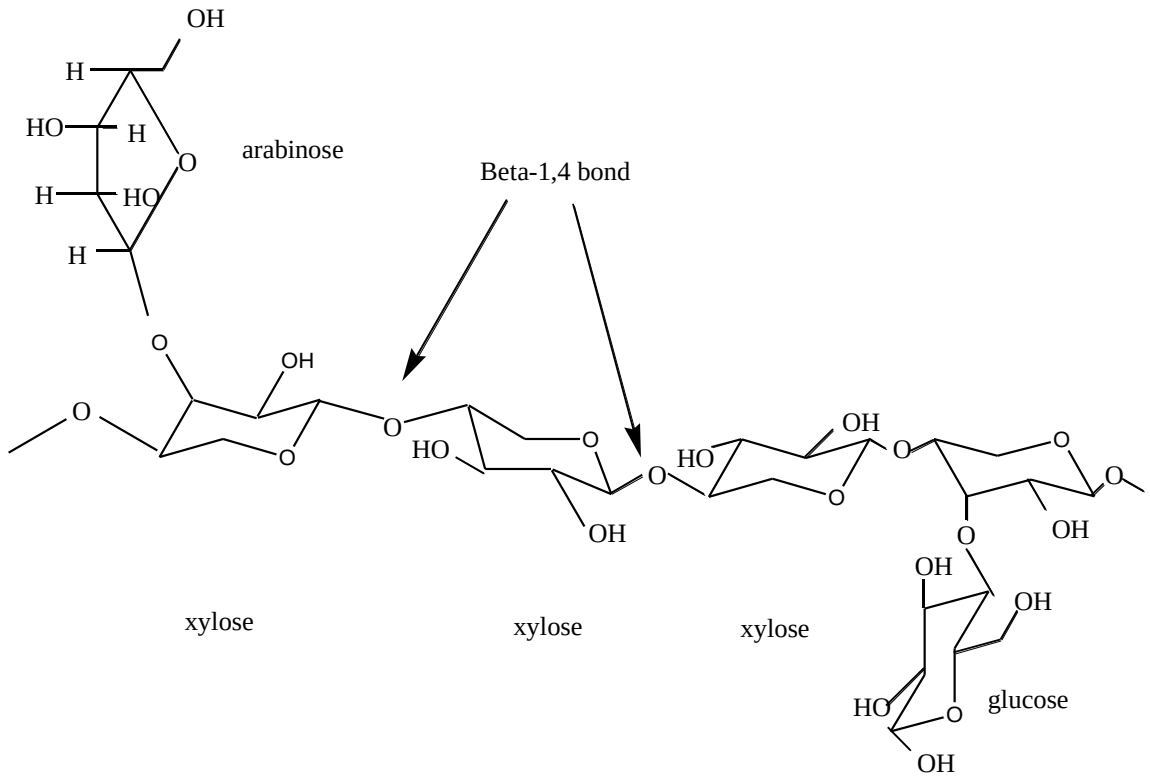

Figure 2.2 Structure of hemicellulose [SMRI, 2011].

The reaction behaviour of hemicellulose during gasification is similar to that of cellulose.

2.2.3 Lignin

Lignin is a three dimensional polymer of three different phenyl-propane precursor monomers: p-coumaryl, coniferyl and sinapyl alcohols [Amen-Chen *et al*., 2001]. They are joined together by aryl-aryl, alkyl-aryl, and alkyl-alkyl ether bonds. This polymer is imbedded in the cellulose/hemicellulose structure acting as a 'glue-like' material. It helps impart rigidity and offers further protection to the biomass against microbial and chemical attack [Sugar Milling Research Institute, 2008]. Figure 2.3 (a) shows the structure of this compound (lignin).

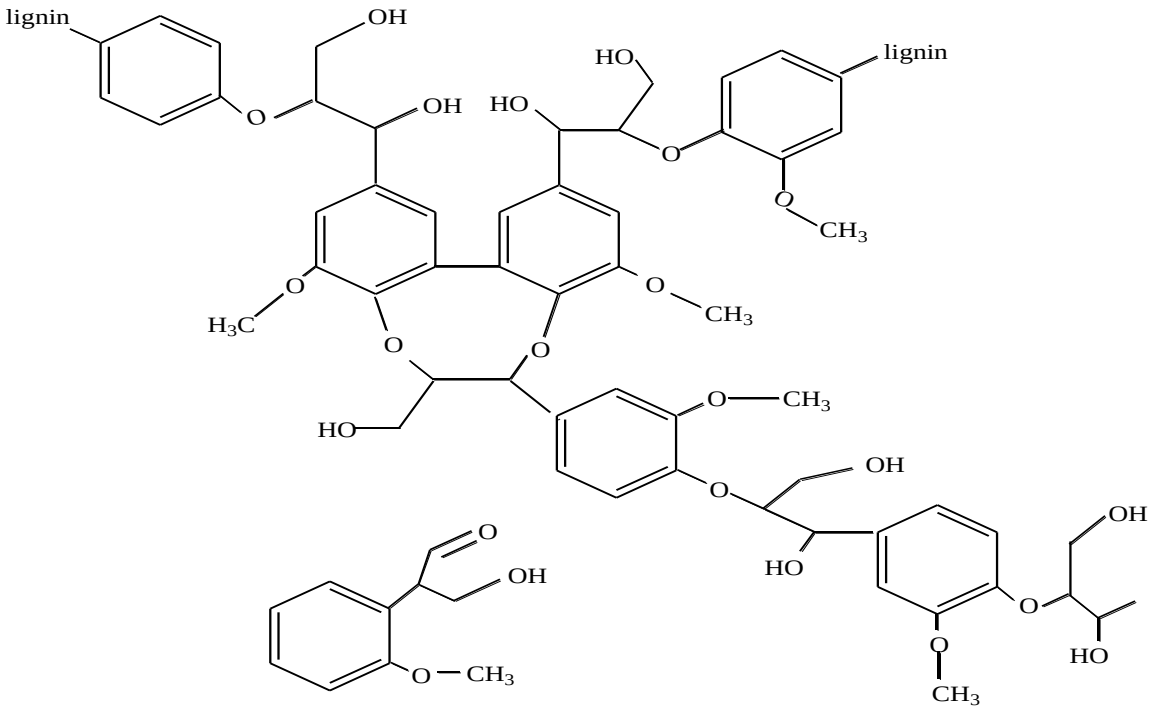

Figure 2.3 (a) Structure of Lignin [SMRI, 2011].

Figure 2.3 (b) shows the structures of the phenyl – propane precursor monomers of lignin.

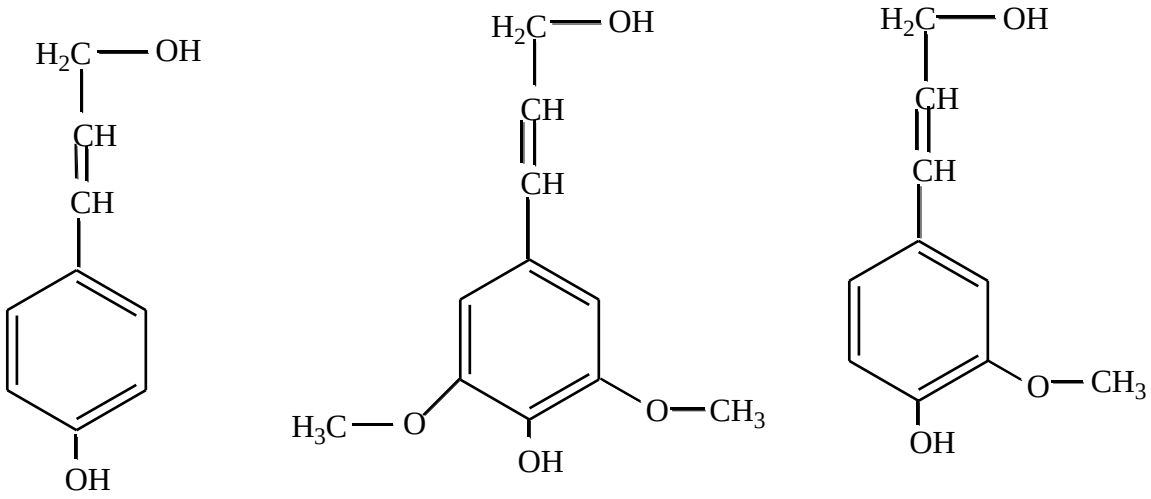

Figure 2.3 (b) Structures of the Phenyl – propane precursor monomers of lignin [SMRI, 2011].

The main gas products from lignin during gasification are CO_2 and CH_4. This is because as heat is applied the decomposition of formaldehyde and the dealkylation of the side chain of the alkyphenols occur, owing to which the main gas products obtained are CO_2 and CH_4.

2.2.4 Ash

Ash is typically the inorganic component of the biomass. It is usually determined using the gravimetric method or the microwave digestion method (EPA method). It can also be determined using the expression:

$$AC = \left(\frac{W_{ash}}{W_{biomass}} \right) \times 100\% \quad (1)$$

where:

AC = Ash Content

W_{ash} = Mass of the ash

$W_{biomass}$ = Mass of the biomass material (sugarcane bagasse) before burning.

The total ash content in the biomass and the chemical composition of the ash affects its behaviour under high temperatures of gasification as part of the ash in the biomass volatilizes. For example, melted ash may cause problems in both combustion and gasification reactors. These problems may vary from clogged ash – removal caused by slagging ash to severe operating problems when fluidized – bed systems are used. Silicon, magnesium, calcium, potassium and phosphorus are the major ash – forming elements in biomass. Agglomeration and slagging of ash in fluidized – bed gasifiers occur at high temperatures, typically above 800ºC [Gustafsson, 2011]. Several mechanisms have been suggested for the agglomeration in fluidized – bed gasification of biomass one of which is the formation of silicates of alkali and alkali earth metals with low melting temperature [Baxter *et al*., 1998]. Problems associated with agglomeration of ash are usually common with bed materials that use silica sand [Gustafsson, 2011].

2.2.5 Protein

Protein is typically the nitrogen containing compounds of the biomass. It is difficult to measure directly from the biomass material. The protein content of biomass is estimated by measuring the total nitrogen in the biomass. This can be achieved by combustion or the Kjeldahl method (method for quantitative determination of nitrogen). Sugarcane bagasse contains low crude protein content [SMIR, 2008].

2.2.6 Volatile matter content

Volatile matter content refers to part of the biomass that is released when the biomass is heated (up to 400 to 500°C). During this heating process the biomass decomposes into volatile gases and solid char. Biomass materials typically have high volatile matter content (up to 80%) [Diebold, 1985].

2.2.7 Moisture content

Moisture refers to the quantity of water in the biomass material. It is determined on a dry or wet basis using gravimetric method. The weight % in dry or wet basis of the biomass moisture content can also be determined by the expression:

On a dry basis:

$$MC = \left(\frac{W_{wet}}{W_{dry}} - W_{dry} \right) \times 100\% \quad (2)$$

where:

MC = Moisture Content

W_{wet} = Mass of the biomass material (sugarcane bagasse) in wet basis

W_{dry} = Mass of the biomass material (sugarcane bagasse) in dry basis.

On a wet basis:

$$MC = \left(\frac{W_{wet}}{W_{wet}} - W_{dry} \right) \times 100\% \quad (3)$$

Moisture content affects the efficiency of the system. From 0 up to 11% moisture content the highest conversion efficiency is achieved (optimal gasification is obtained). From 12 to 20% moisture content the material is suitable for the biomass gasification and above 21% moisture content the material is not suitable for gasification [Mamphweli, 2009]. Because moisture content affects the value of biomass as a fuel, the basis on which the moisture content is measured must always be mentioned. This is particularly important because biomass materials exhibit a wide range of moisture content (on a wet basis). The maximum allowable moisture content must be 21% to ignite the fuel and extract energy from it [Quaak *et.al.*, 1999 and Mamphweli, 2009]. High moisture content reduces the higher heating value of biomass materials. Biomass materials always contain some amount of water, which is released as vapour upon heating. This implies that some of the heat liberated during the chemical reaction is absorbed by the evaporation process. For this reason, the higher heating value decreases as the moisture content of the biomass increases which therefore mean lower content of combustible matter per kilogram of biomass fuel.

2.2.8 Extractables

Extractables are the non-structural materials present in the biomass that can be easily extracted. Sugarcane bagasse would contain traces of pol and soluble ash.

The basic composition of sugarcane bagasse is presented in table 2.4.

Table 2.4 Basic composition of bagasse [Bon, 2007, Paturau, 1989 and Trickett and Neytzell-de wilde, 1982].

(%) Cellulose	(%) Hemicellulose	(%) Lignin	(%) Ash
37	28	21	Unreported
26 – 47	19 – 33	14 – 23	1 – 5
38	33	22	3

The chemical composition of sugarcane bagasse is also shown in tables 2.5 and 2.6 respectively.

Table 2.5 Elemental composition of SB (in wt % moisture and ash free) [Rolando *et al*., 1995].

Bagasse dp (mm)	C	H	N	O
0.3 – 0.5	46.8	6.2	0.3	46.7
0.86 – 1.0	47.3	6.2	0.3	46.2

Table 2.6 Ash (in wt %, Moisture free) and Moisture (in wt %) content in bagasse [Rolando *et al*., 1995].

dp in mm	Ash	Moisture
0.30-0.50	2.4	6.8
0.50-0.86	1.0	6.9
0.86-1.00	0.9	7.0
1.00-1.35	1.5	6.9

Table 2.6 shows the ash and moisture level in the various sizes of bagasse. This difference in the ash and moisture content of the various sizes of bagasse is dependent on the source of the sugarcane plant.

The hemicellulosic fractions could be isolated by sequential extraction according to the scheme in figure 2.4.

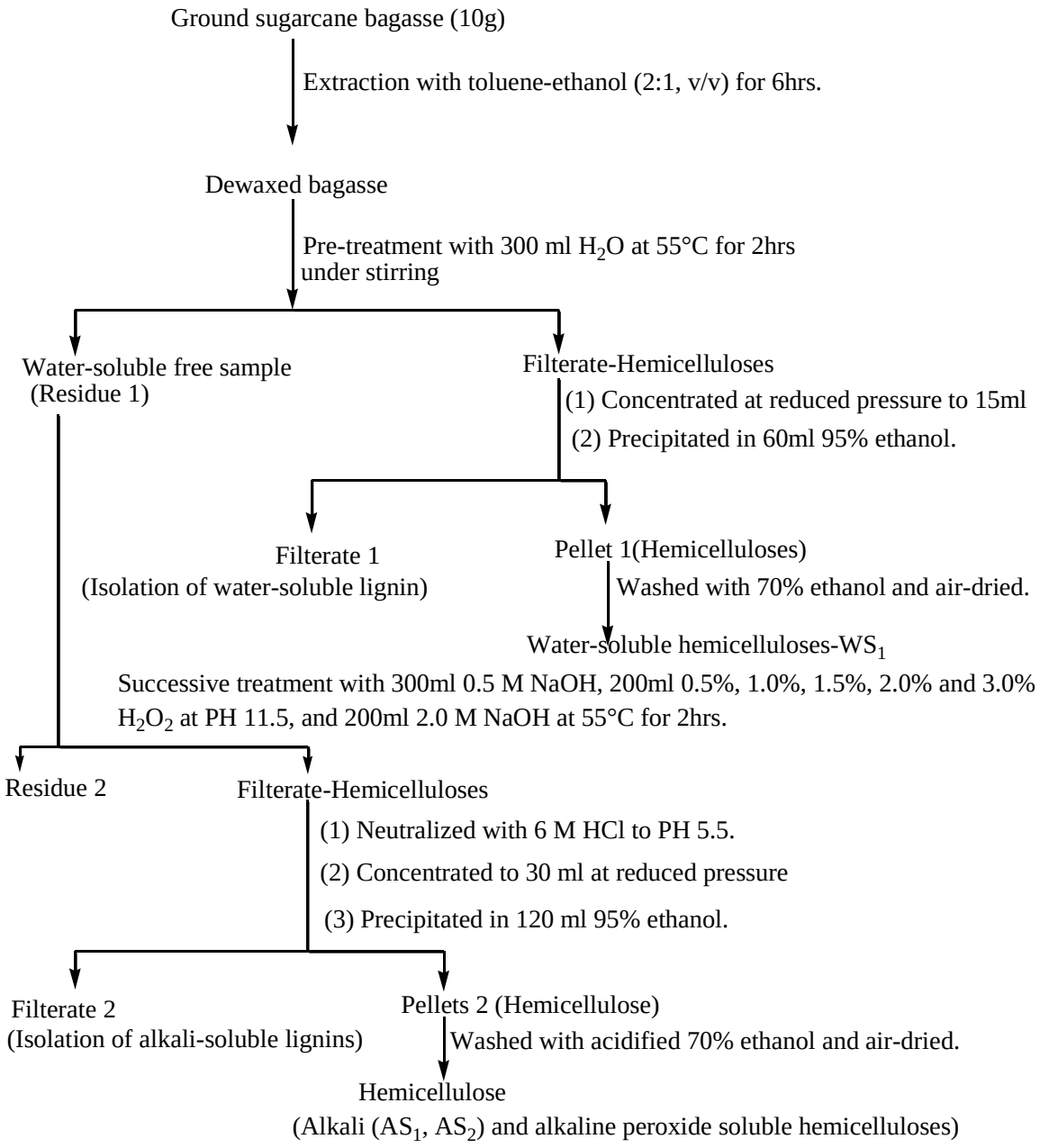

Figure 2.4 Scheme for Fractional isolation of hemicelluloses from dewaxed bagasse [Sun *et al*; 2004].

2.3 THE PROCESS OF CRUSHING SUGARCANE AND THE RESULTANT BAGASSE

The basic process of sugarcane crushing involves breaking up the hard nodes of the cane and flattening of the stems. The resultant cane residue (bagasse) left is dried and often used as fuel for the sugar production process. Most artisanal producers of sugar make use of a simple crusher consisting of three metal rollers that is driven by either animal or diesel power. A crusher driven by a single ox can be expected to process around 50kg of cane per hour while a 5HP diesel set could process around 300kg of cane per hour. The rollers are set vertically. Many machines have horizontal rollers [Schumacher Centre for Technology and Development, 2010].

On an industrial scale, once harvested sugarcane arrives at the mill where it is tipped on to a cane carrier which transports the cane billets to a shredder. The sugarcane is reduced and shredded into fibrous material and the juice cells ruptured. The sweet juice is then concentrated and crystallized to produce sugar. Cane shredding actually involves the mechanical disruption of the stalk to allow for the juice to be more easily pressed and diffused from the cane.

Two valuable by-products are generated by this process:

i. Bagasse, which is the fibrous material left after the sugarcane has been crushed
ii. Molasses, which is the syrup left over after sugar crystals have been formed.

However, the topic of interest in this study is the bagasse which this review of literature is concerned about. The resultant bagasse obtained is utilized as a valuable new material, not only for the manufacture of paper but also for electricity production [Akhtar, 1990]. Furthermore, in some countries around the world, the sludge left over after removing the cellulose fibers in creating bagasse is used to power the mills. The resulting CO_2 emissions in burning bagasse are equal to the amount of CO_2 that the sugarcane plant used up from the atmosphere during its photosynthesis. Consequently, the resultant heat from this process appears to be greenhouse gas-neutral [www.bhumiproducts.com, 2012]. Experimentally, one ton of sugarcane crushed can produce about 280kg bagasse with 50% moisture. Since plenty of bagasse is produced per unit of sugarcane crushed, no particular attention has been paid to its economy [Akhtar, 1990].

2.4 THE AVAILABILITY AND CURRENT USE OF SUGARCANE BAGASSE IN SOUTH AFRICA

South Africa, which is currently a water-stressed country and predicted to become water scarce by the year 2025, has one of the highest per capita greenhouse gas CO_2 emissions in the world because it relies heavily on its coal resources for energy [UNECA, 1999 and SADME, 2005].

Consequently, energy issues are included among critical aspects in the government's objective to transform the nation into a more sustainable country. Working to develop a more efficient energy system by implementing technologies that make use of bagasse is therefore timely and valuable to both South Africa and the world as a whole.

The capacity of electricity generation in South Africa is approximately 40 000MW, with a portion of this capacity supplied to meet non-South African demand. It has also been estimated that South African demand for electricity will be 42 000MW by 2013 [Department of Minerals and Energy, 2005]. The White Paper on Renewable Energy has set a target of 10 000GWh to be achieved by the year 2013, which is approximately 4% of the projected electricity demand for that year [Huletts, 2012].

The sugarcane industry in South Africa thrives along the Eastern Coast in the provinces of Kwazulu-Natal, Mpumalanga, and the Eastern Cape. It is estimated that 2.5 million tons of sugar and 20.7 million tons of raw, crushed sugarcane are produced per season [South African Sugar Association, 2011]. Currently, South African sugarcane processing mills burn most of the bagasse to fuel the boilers; other uses of the bagasse include biogas, paper and pulp, consumption alcohol, and animal feed [Lyne, 2006]. In South Africa, however, the sugar industry is exploring possible processing options to add value to sugarcane bagasse. The South African sugar industry produces about 8 million tons of bagasse per year [Energy statistics database, 2008]. Some of this bagasse is burnt in boilers to generate steam for the sugar factories. However, recent improvements in boiler technology has led to a significant amount of surplus bagasse becoming available, and approximately 50% of the bagasse is sufficient to supply the energy needs for sugar mills using modern boilers [Botha and Blottnitz, 2006 and Lavarack *et al*., 2002]. The remaining bagasse can be used to produce by-products, e.g. bioethanol, pyrolysis oil and char or electricity.

The South African sugar industry and ancillary industries relying on sugar or its by-products have been involved in value-added products for many years. A number of authors previously reviewed a number of these enterprises and their typical applications, including bagasse derived products. Bagasse has been used as the raw material for a number of products and further processing in South Africa [Cleasby, 1968; Andrews, 1977; Bernhardt, 1993]. These include:

2.4.1 Animal feed. Bagasse is a source of roughage which compares favourably with ground maize cobs and cottonseed hulls in terms of digestibility. The absorbent properties of dried, milled bagasse make it an ideal carrier for molasses, a relatively inexpensive energy source containing minerals and vitamins. Two commercial animal feed producers in South Africa use combined bagasse and molasses. Voermol Feeds was commissioned adjacent to the Maidstone mill in 1963 [Anon, 1963] and Molatek Feeds adjacent to the Malelane mill.

2.4.2 Pulp and Paper. Although bagasse is not as good as timber for the production of paper due to the higher ash content and shorter fibres, the first pulp and paper operation was commissioned in 1956 at the Ngoye Paper Mill adjacent to the Felixton sugar mill. After a particularly well-documented study this plant undertook one of the first industrial applications of the Ritter biopulping treatment of bagasse fibre to avoid deterioration. The mill is today part of the Mondi group. The world's first commercial production of coated paper from bleached bagasse pulp was brought on stream at the Stanger Pulp and Paper mill in 1976 [Bruijn *et al*., 1974, Anon, 1975 and Andrews, 1977]. This paper mill,

which also produces tissue, is attached to the Gledhow sugar mill that provides some of the bagasse for depithed fibre. The paper mill is now part of the Sappi group.

2.4.3 Furfural. The only plant in South Africa making chemicals directly from bagasse is the furfural (2-furfuraldehyde) plant that was commissioned in 1972 at Sezela by Smithchem (Pty) Ltd [Anon, 1979b and Anon, 1973]. A furfural alcohol factory was commissioned in 1980 and most of the furfural produced is converted to the alcohol and exported [Anon, 1979b and Bernhardt, 1993]. Furfural has recently been registered for use as a nematicide (GroupGuard®) by Illovo and further use is expected [Cropguard, 2012]. Other chemicals isolated and further processed include acetoin, diacetyl and 2, 3-pentanedione [Illovo, 2012]. Bagasse residue is fed back to the sugar mill boilers as fuel.

2.4.4 Particle Board is conventionally made from timber products. Bagasse fibre can be bound together with resin to form bagasse particle board. This was produced by Hulsakane Ltd (a Hulett company) from 1972 to 1975. The plant was located at the Amatikulu sugar mill that provided depithed bagasse. The board was used in the construction industry [Anon, (1972).] until the factory ceased production due to mechanical and profitability constraints. At around the same time, a second board plant came on stream producing a board having smooth surfaces on both sides in contrast to the Hulsakane board [Andrews, 1977]. It is currently made by Ultraboard from bagasse at the Malelane mill and is used in furniture making as backing board [Anon, 1978].

Other value-added products applications that have had varied success in South Africa includes:

2.4.5 Waxes which have historically been recovered from the filter mud of milling factories processing green cane using simple solvent extraction. These muds contain about half the wax present in cane. Solvents used include benzene, toluene and petroleum ethers. Extraction from muds rather than from bagasse has been preferred because lower volumes are processed. One of the reasons for the establishment of The Natal Cane By-Products (NCBP) in 1917 was for the commercial scale extraction of cane wax at the Esperanza mill. Further plants were installed at Renishaw, Illovo and Tongaat with a central refining plant at Umgeni, which later became uneconomic [Bernhardt, 1993]. A pilot scale plant was erected at Darnall in the late 1950`s. This burnt down and was never replaced [Anon, 1955 and Mitchell, 1979].

2.4.6 Sugar alcohols including sorbitol, mannitol and xylitol are prepared by the hydrogenation of glucose, fructose and xylose. These alcohols can also be used as the starting point for the preparation of glycols and other chemicals. The Natal Cane By-Products (NCBP) erected a sorbitol and mannitol plant in 1980 [Anon, 1984] that ceased production in the early 1990s. TSB were partners in the Polyol Partners consortium that researched glycols production from molasses in the 1990s. A pilot plant was established at Malelane with funding from the Industrial Development Corporation [Friobjarnarson *et al.*, 2003].

2.5 THE BIOMASS GASIFICATION PROCESS

Biomass has been a major energy source, prior to the discovery of fossil fuels like coal and petroleum. Even though its role is presently diminished in developed countries, it is still widely used in rural communities of the developing countries for their energy needs

in terms of cooking and limited industrial use. Biomass, besides using in solid form, can be converted into gaseous form through gasification route.

Biomass is a natural substance available, which stores solar energy by the process of photosynthesis in the presence of sunlight. It chiefly contains cellulose, hemicellulose and lignin, with an average composition of $C_6H_{10}O_5$, with slight variations depending on the nature of the biomass. Theoretically, the ratio of air-to-fuel required for the complete combustion of the biomass, defined as the stoichiometric combustion is 6:1 to 6.5:1, with the end product being CO_2 and H_2O. However, biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane (CH_4). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and spark ignition), can be used as substitutes for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol – an extremely attractive chemical which is useful both as a fuel for heat engines as well as chemical feedstock for industries [Reed *et al*., 1982].

Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel. Besides, there is a problem that solid wastes (available on the farm) are rarely in a form that can be readily utilized economically, e.g. wood wastes can be used in hog fuel boilers but the equipment is expensive and energy recovery is low [Eggen and Kraatz, 1976]. During gasification, combustion is carried out at sub-stoichiometric conditions with air-to-fuel ratio being 1.5:1 to 1.8:1. The gas so obtained is called producer gas, as

mentioned earlier, which is combustible. This process is made possible in a device called gasifier. However, the key to gasifier design is to create conditions such that biomass is reduced to charcoal and charcoal is converted at suitable temperature to produce CO and H_2.

In a gasifier, the biomass material undergoes several different processes. The following major reactions take place in the gasifier [Kumar *et al*., 2009]:

i. Drying of fuel – This process occurs at around 100°C to 140°C. Typically the resulting steam is mixed into the gas flow and may be involved with subsequent chemical reactions, notably the water-gas reaction if the temperature is sufficiently high enough.
ii. Pyrolysis – This process occurs at around 400-600°C. Volatiles are released and char is produced, resulting in up to 70% weight loss for coal. The process is dependent on the properties of the biomass and determines the structure and composition of the char, which will then undergo gasification reactions.
iii. Combustion – This process occurs as the volatile products and some of the char reacts with oxygen to primarily form carbon dioxide and small amounts carbon monoxide, which provides heat for subsequent gasification reactions. Combustion takes place at around 800 – 1500°C.

$$C + O_2 \rightarrow CO_2 \qquad (+393 \text{ MJ/kg moles}) \tag{4}$$

$$2H_2 + O_2 \rightarrow 2H_2O \ (-242 \text{ MJ/kg mole}) \tag{5}$$

iv. Reduction – The reduction or reaction zone, inside the inverted truncated cone below the throat, where the carbon dioxide from the combustion as well as the water vapour is turned into carbon monoxide and hydrogen. The gasification process occurs as char reacts with carbon and steam to produce carbon monoxide and hydrogen. During this process only a small percentage of methane is formed, since the temperature is much too high for the ready formation thereof. During reduction, hot gas temperature is also substantially reduced. If the ash were not removed continuously through the ash grate, ash would then build up inside the reduction cone and contaminate the reduction charcoal. This would quickly lead to overheating, which if not stopped in time could destroy the hearth. The automatic variable-speed ash grate prevents over-heating, provided it operates at the correct speed for a certain fuel. The products of partial combustion (water, carbon dioxide and incombustible partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place [Solar Energy Research Institute, 1979].

$$C + CO_2 \rightarrow 2CO \qquad (-164.9 \text{ MJ/kg mole}) \qquad (6)$$

$$C + H_2O \rightarrow CO + H_2 \qquad (+122.6 \text{ MJ/kg mole}) \qquad (7)$$

$$C + 2H_2 \rightarrow CH_4 \qquad (+75 \text{ MJ/kg mole}) \qquad (8)$$

$$CO_2 + H_2 \rightarrow CO + H_2O \qquad (-42.3 \text{ MJ/kg mole}) \qquad (9)$$

Reactions (6) and (7) are the main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the

reduction zone are normally 500 - 700°C. The lower the reduction zone temperature (~ 700-800°C), the lower the calorific value of the gas.

Since majority of fuels like wood and biomass residue do have large quantities of tar, the downdraft gasifier is preferred over others. Figure 2.5 show a flow diagram of the biomass gasification process.

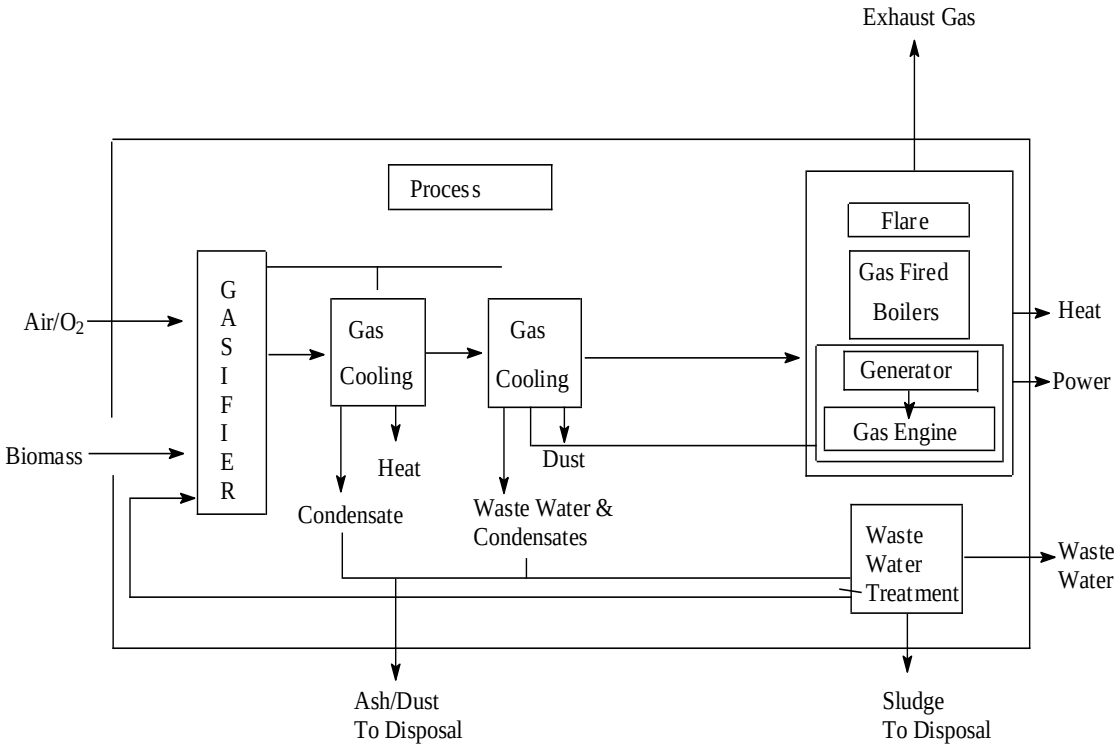

Figure 2.5 The Biomass gasification process [Biomass Gasification, 2012].

2.5.1 Types of gasifiers

Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it. A characteristic of the

various gasifiers is the way in which the biomass material is brought into contact at the gasification stage.

There are many types of gasifiers which includes the Fixed-Bed Updraft or Counter-Current gasifier, the Fixed-Bed Downdraft or Co-Current gasifier, the Fixed-Bed Crossdraft gasifier and the Fluidized-Bed gasifiers. However, the choice of gasifier type depends on the type of fuel to be gasified and the end use of the gas produced.

All systems show relative advantages and disadvantages with respect to fuel type, application and simplicity of operation, and for this reason each will have its own technical and economic advantages in a particular set of circumstances.

2.5.1.1 The Fixed-Bed Updraft or Counter-Current Gasifier is the oldest and simplest type of gasifier. It is schematically shown in Figure 2.6. In this type of reactor, the biomass material is usually fed at the top of the reactor and moves downward as a result of its conversion and removal of ashes. The air intake is at the bottom and the gas leaves at the top. The biomass material moves counter to the gas flow and passes through drying, distillation, reduction and the hearth zones. In the drying zone, the biomass material is dried. In the distillation zone, it is decomposed into volatile gases and solid char. The heat for pyrolysis and drying is mainly supplied by the upward-flowing producer gas and partly by radiation from the combustion zone. Near the grate at the bottom the combustion reactions occur, which are followed by reduction reactions somewhat higher up in the gasifier. In the upper part of the gasifier, heating and pyrolysis of the feedstock occur as a result of heat transfer by forced convection and radiation from the lower zones.

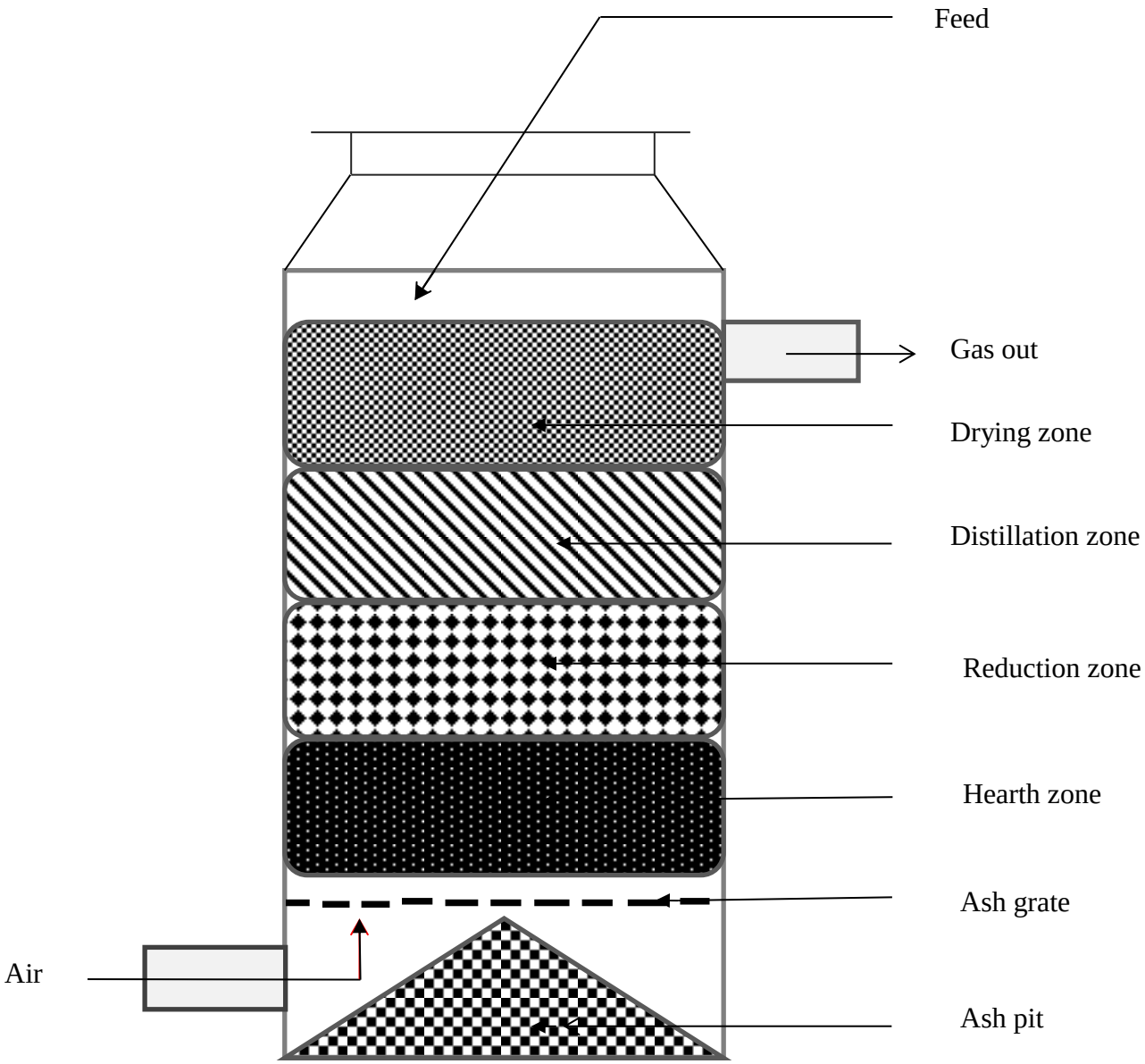

Figure 2.6 Fixed-bed Updraft gasifier or Counter Current gasifier

[Adopted from FAO Corporate Document Repository, 1986].

The tars and volatiles produced during this process will be carried in the gas stream. Ashes are removed from the bottom of the gasifier. The major advantages of this type of gasifier are its simplicity, high charcoal burn-out and internal heat exchange leading to low gas exit temperatures and high equipment efficiency, as well as the possibility of

operation with many types of feedstock (sawdust, cereal hulls, etc.). The fixed – bed updraft gasifier also have the advantage of tolerating fuel with high moisture content because the air or gasifying agent is introduced from the bottom of the gasifier and the gas exit is at the top of the gasifier. This allows for high rate of heat transfer because the hot gas from the combustion zone of the gasifier interacts with the biomass material drying the material on its way out. Major drawbacks result from the possibility of "channelling" in the equipment, which can lead to oxygen breakthrough and dangerous, explosive situations and the necessity to install automatic moving grates, as well as from the problems associated with disposal of the tar-containing condensates that result from the gas cleaning operations. The latter is of minor importance if the gas is used for direct heat applications, in which case the tars are simply burnt.

2.5.1.2 Fixed-Bed Downdraft or Co-Current Gasifier. A solution to the problem of tar entrainment in the gas stream has been found by designing co-current or downdraft gasifiers, in which primary gasification air is introduced at or above the combustion zone in the gasifier. The producer gas is removed at the bottom of the apparatus, so that fuel and gas move in the same direction, as schematically shown in Figure 2.7.

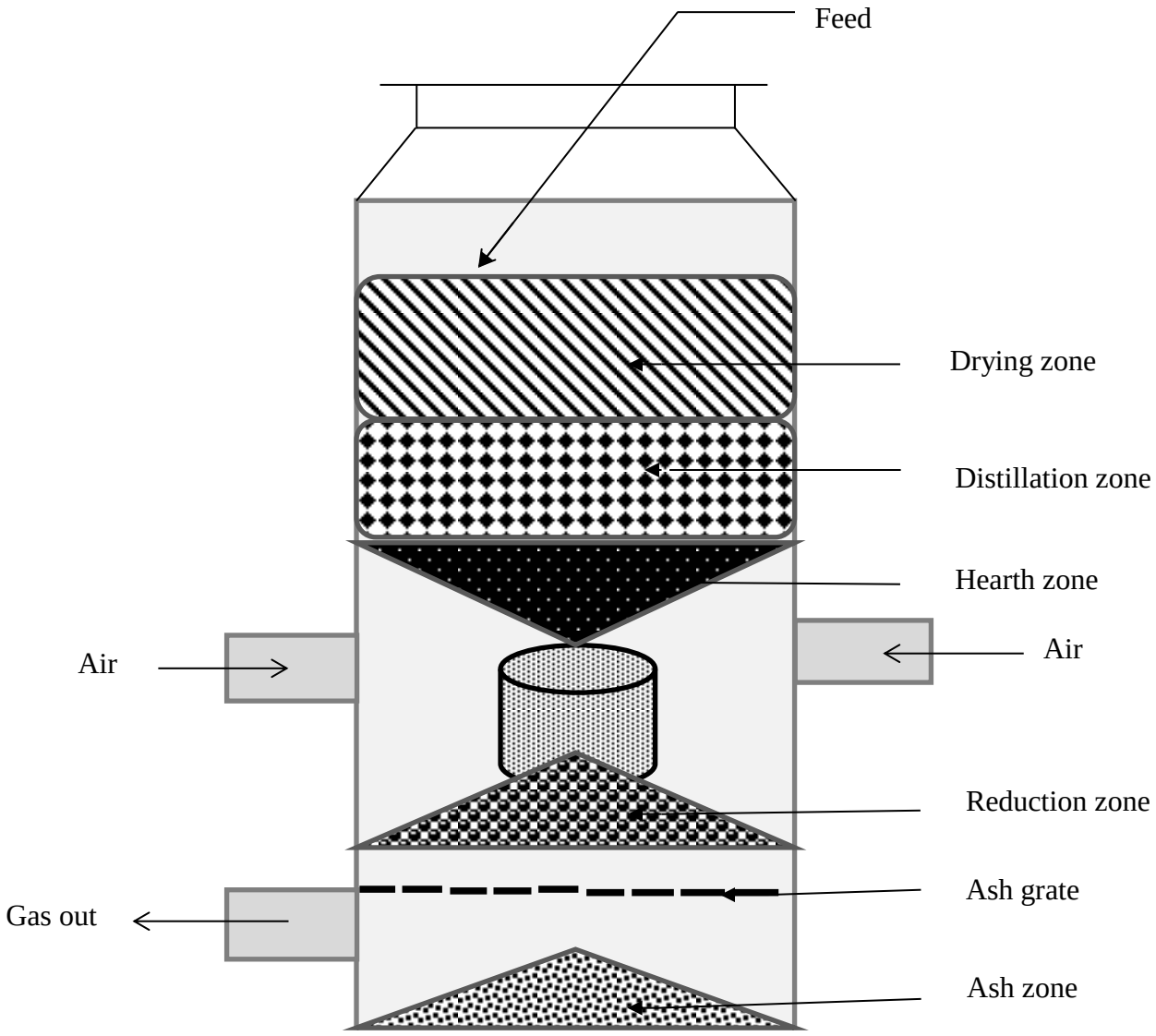

Figure 2.7 Fixed-bed Downdraft gasifier or Co-Current gasifier

[Adopted from FAO Corporate Document Repository, 1986].

On their way down the acid and tarry distillation products from the fuel must pass through a glowing bed of charcoal and therefore are converted into permanent gases hydrogen, carbon dioxide, carbon monoxide and methane. Depending on the temperature of the hot zone and the residence time of the tarry vapours, a more or less complete

breakdown of the tar is achieved. The main advantage of downdraft gasifiers lies in its possibility of producing a tar-free gas suitable for engine applications.

In practice, however, a tar-free gas is seldom if ever achieved over the whole operating range of the equipment reason being that not all gases pass through the hottest zones of the gasifier. Tar – free operating turn – down ratios of a factor 3 are considered standard; a factor 5 – 6 is considered excellent [FAO forestry paper, 1986]. Because of the lower level of organic components in the condensate, downdraft gasifiers suffer less from environmental objections than updraft gasifiers. A major drawback of downdraft equipment lies in its inability to operate on a number of unprocessed fuels. In particular, fluffy, low density materials give rise to flow problems and excessive pressure drop, and the solid fuel must be pelletized or briquetted before use. Downdraft gasifiers also suffer from the problems associated with high ash content fuels (slagging) to a larger extent than updraft gasifiers. Minor drawbacks of the downdraft system, as compared to updraft, are somewhat lower efficiency resulting from the lack of internal heat exchange as well as the lower heating value of the gas. Besides this, the necessity to maintain uniform high temperatures over a given cross-sectional area makes impractical the use of downdraft gasifiers in a power range above about 350 kW (shaft power) [Eggen and Kraatz, 1976].

2.5.1.3 The Fixed-Bed Crossdraft Gasifier. Schematically illustrated in Figure 2.8 is an adaptation for the use of charcoal. Charcoal gasification results in very high temperatures (1500 °C and higher) in the oxidation zone which can lead to material problems. In cross draft gasifiers insulation against these high temperatures is provided by the fuel (charcoal) itself. Advantages of the system lie in the very small scale at which it can be

operated. Installations below 10 kW (shaft power) can under certain conditions be economically feasible. The reason is the very simple gas-cleaning train (only a cyclone and a hot filter) which can be employed when using this type of gasifier in conjunction with small engines. A disadvantage of cross-draft gasifiers are their minimal tar-converting capabilities and the consequent need for high quality (low volatile content) charcoal.

It is because of the uncertainty of charcoal quality that a number of charcoal gasifiers employ the downdraft principle, in order to maintain at least a minimal tar-cracking capability.

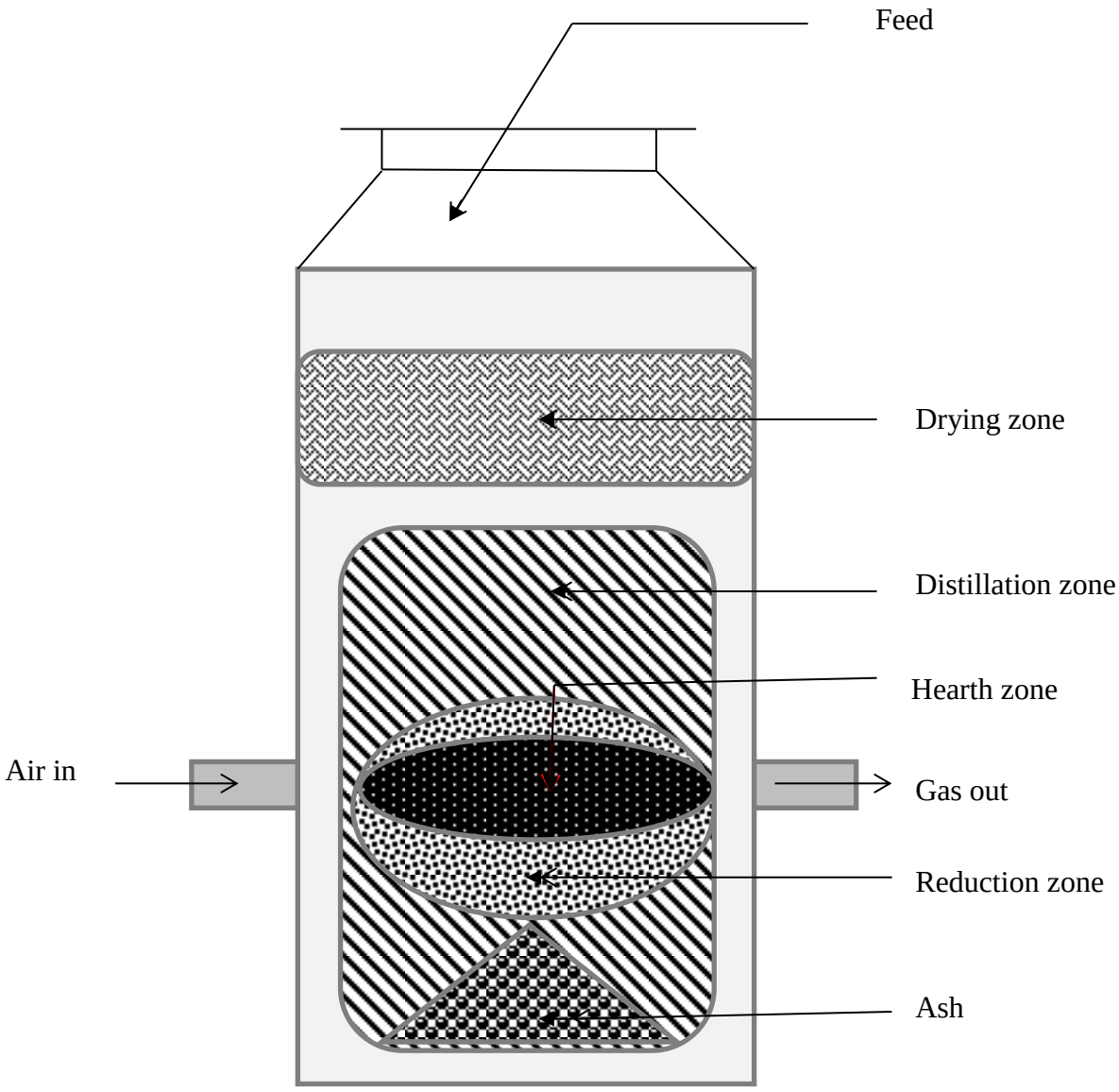

Figure 2.8: Schematic diagram of a Crossdraft gasifier

[Adopted from FAO Corporate Document Repository, 1986].

This type of gasifier, although, more advantageous than the updraft and downdraft gasifiers, are not ideal to use. They have many varied disadvantages such as high exit gas

temperature, poor CO_2 reduction and high gas velocity which are consequences of the design [www.enggcyclopedia.com, 2012]. Unlike the updraft and downdraft gasifiers, the ash zone of the crossdraft gasifier as well as its combustion and reduction zones are separate. The characteristics of the design limits the type of feedstock to be used which is restricted to only fuels with low ash content such as wood, charcoal and coke [www.enggcyclopedia.com, 2012]. Concentrated zones of the crossdraft gasifier operate at temperatures up to 1200°C which makes its load following ability quiet good. The start up time of the crossdraft gasifier, much faster than that of the updraft and downdraft gasifiers, is about 5 – 10 mins. The relatively higher temperatures in the crossdrfat gasifier has an impact on the exit gas composition such as high CO and low H_2 as well as low CH_4 content when dry fuel such as charcoal is used. The crossdraft gasifier operates well on dry air blast and dry fuel [www.enggcyclopedia.com, 2012].

2.5.1.4 Fluidized Bed gasifier. Was originally developed to overcome operational problems of fixed-bed gasification of biomass materials with high ash content, lack of bunkerflow, slagging and extreme pressure drop over the gasifier. Compared with fixed-bed gasifiers, the gasification temperature is relatively low (approximately 750 to 900°C). In fixed-bed gasifiers, the temperature in the combustion zone may be as high as 1,200°C, and in charcoal gasifiers it may be up to 1,500°C. However, in the fluidized bed gasifier, air is blown through a bed of solid particles at a sufficient velocity to keep the bed in a state of suspension. The bed is originally externally heated and the feedstock is

introduced as soon as a sufficiently high temperature is reached. The fuel particles are introduced at the bottom of the reactor, very quickly mixed with the bed material and almost instantaneously heated up to the bed temperature. As a result of this treatment the fuel is pyrolysed very fast, resulting in a component mix with a relatively large amount of gaseous materials. Further gasification and tar-conversion reactions occur in the gas phase. Because of the low temperatures of the fluidized bed gasifiers, the tar-conversion rates are not very high. Most systems are equipped with an internal cyclone in order to minimize char blow-out as much as possible. Ash particles are also carried over the top of the reactor and have to be removed from the gas stream if the gas is used in engine applications. A schematic of the fluidized bed gasifier is given in figure 2.9.

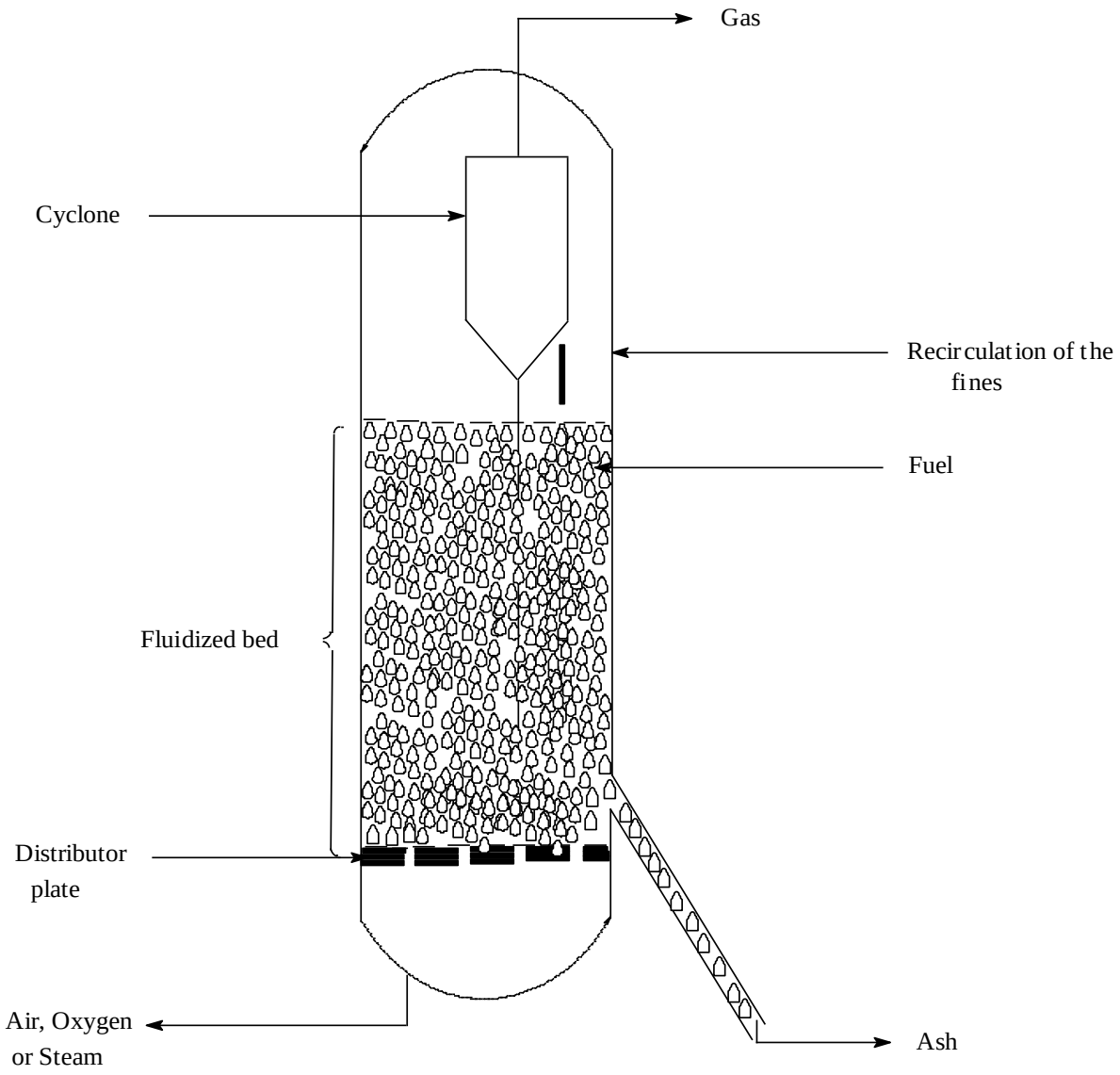

Figure 2.9 Schematic diagram of a Fluidized bed gasifier

[Adopted from FAO Corporate Document Repository, 1986].

The major advantages of fluidized bed gasifiers stem from their feedstock flexibility resulting from easy control of temperature, which can be kept below the melting or fusion point of the ash (rice husks), and their ability to deal with fluffy and fine grained materials (sawdust etc.) without the need of pre-processing. Feeding problems and

instability of the bed as well as fly – ash sintering in the gas channels can occur with some biomass materials. Other limitations of the fluidized bed gasifier include high tar content of the product gas (up to 500 mg/m³ gas) and incomplete carbon burn-out as well as poor response to load changes [FAO Corporate Document Repository, 1986].

2.5.1.5 Entrained flow gasifier. An entrained flow gasifier is characterized by fuel particles dragged along with the gas stream. This generally means high temperatures (typically 1300 – 1500°C), short residence times and small fuel particles (typically < 100 μm). They are often operated under pressure and with pure oxygen. The capacity is often in the order of several hundreds of MW [Van der Drift *et al*., 2004].

The fuels are generally being introduced in the gasifier, after being pressurized, by pneumatic feeding. A movement of the powder is caused by an inert gas which is injected into a burner in the gasifier. The burner functions to realize a good mixing between the feedstock and oxygen creating vortex flow pattern in the burner. Because of short residence time, entrained flow gasifiers operates at high temperatures in order to achieve high carbon conversion. Most entrained flow gasifiers use oxygen rather than air and operate above the slagging temperature. Figure 2.10 presents the schematic diagram of this gasifier.

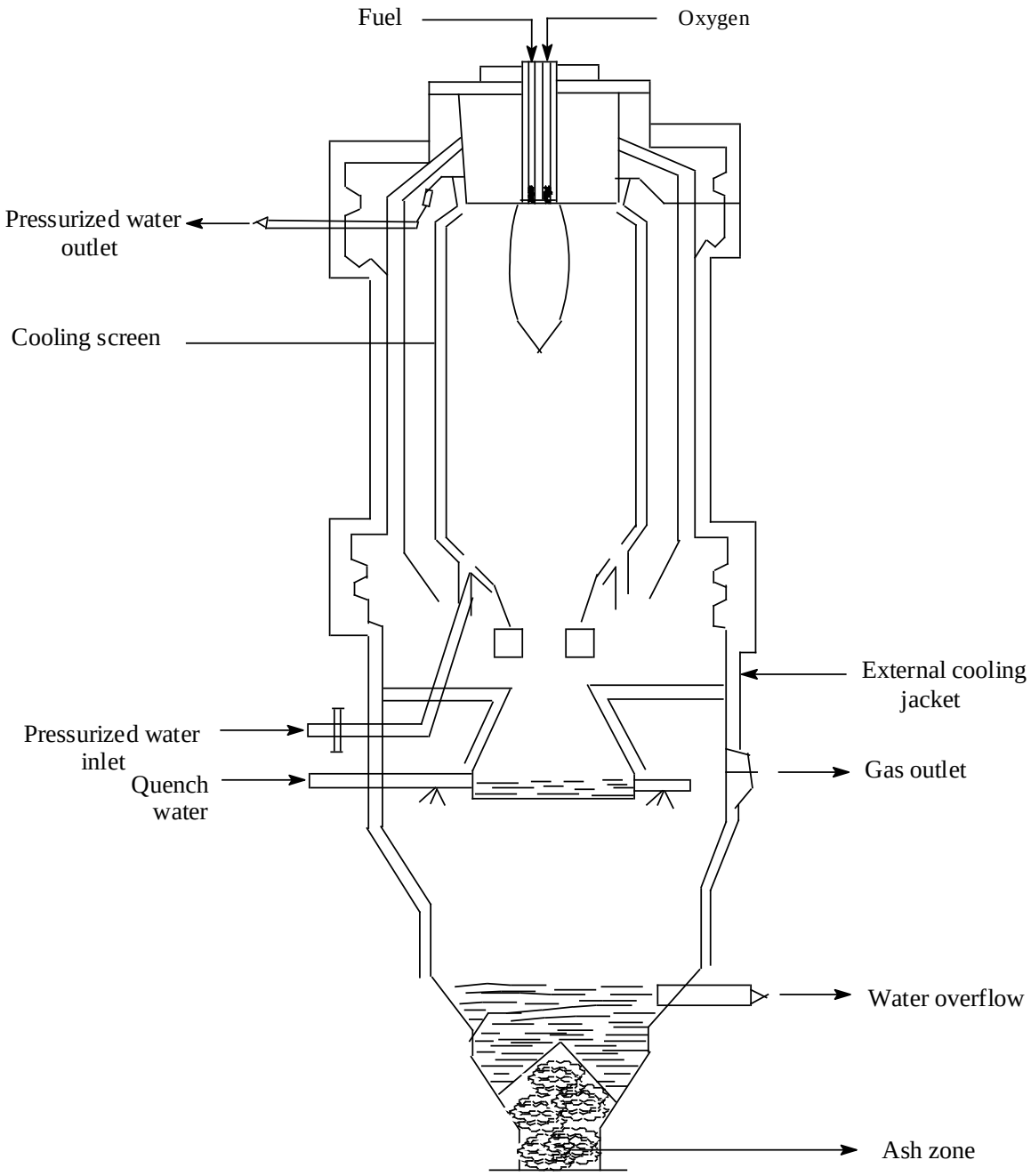

Figure 2.10 Schematic diagram of an Entrained flow gasifier

[Adopted from NETL, 2012].

2.5.1.6 Plasma gasifiers. These uses plasma technologies to convert biomass materials or organic matter into syngas in an oxygen – deficient environment. In plasma gasification, wastes are not combusted as they do in incinerators. They are converted into a fuel gas that still contains the entire chemical and heat energy from the waste. A plasma torch powered by an electric arc is used to ionize gas and catalyze organic matter into synthetic gas and solid waste. Plasma gasifiers are used commercially as a form of waste treatment and have, however, also been tested for the gasification of biomass and solid hydrocarbons such as coal. The process of plasma gasification can both generate electricity while reducing the volume of waste. Figure 2.11 shows the schematic diagram of a plasma gasifier.

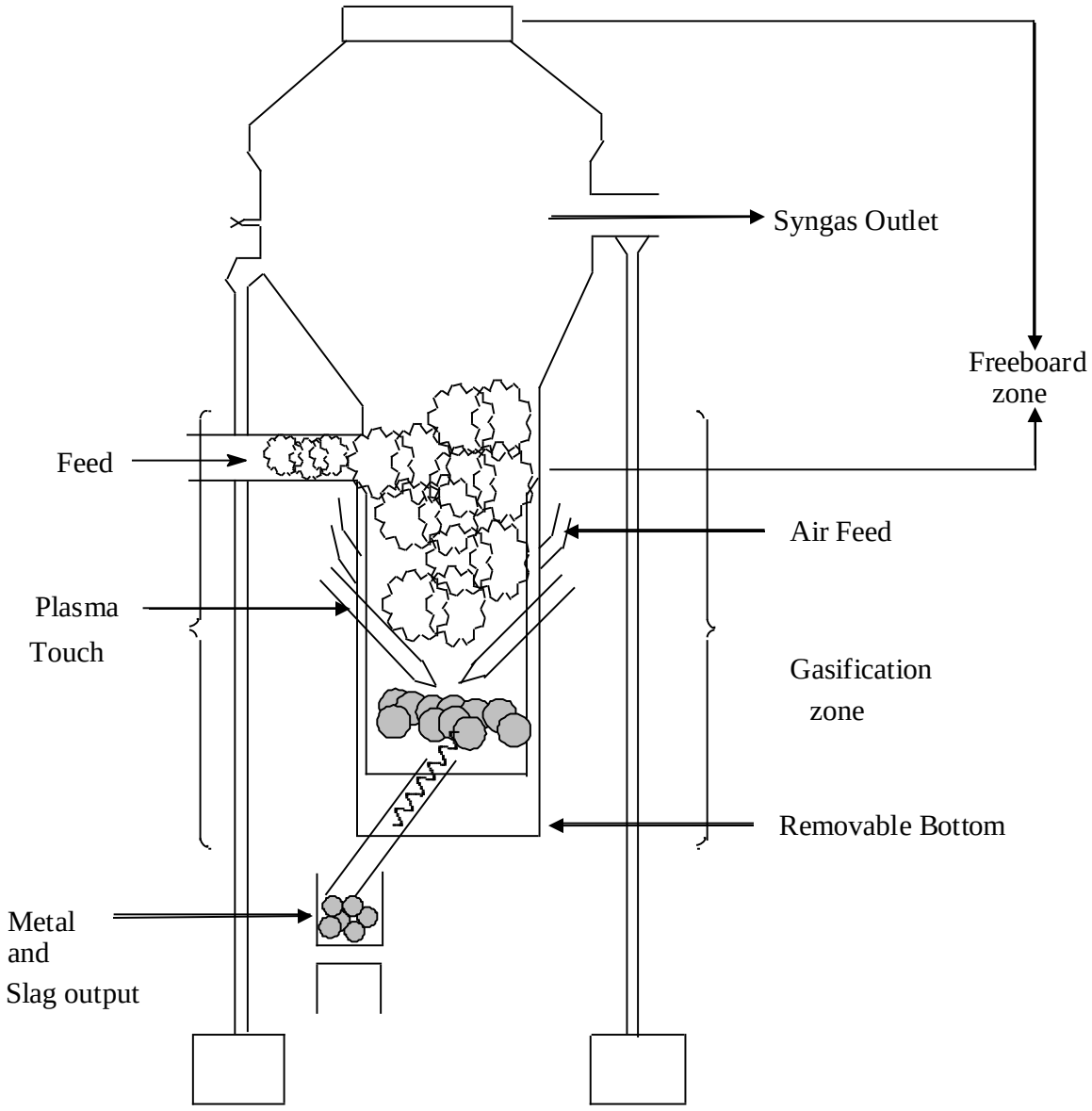

Figure 2.11 Schematic diagram of a Plasma gasifier [Adopted from NETL, 2012].

Plasms gasification takes place at very high temperatures, typically above 6,000ºC, driven by a plasma torch system, which is located at the bottom of the gasifier. The feedstock is broken down into its constituent elements and dramatically increasing the kinetics of the various reactions occurring in the gasification zone, converting all organic

materials into carbon monoxide (CO) and hydrogen (H_2). Any residual materials of inorganic and heavy metals will be melted and produced as a vitrified slag which is highly resistant to leaching [National Energy Technology Laboratory, 2012].

The main advantage of plasma gasifiers lies in its greater feed flexibility which enables the feedstock to be used as fuel without the need for pulverizing. Another advantage of using a plasma gasifier is its high availability and high conversion of feedstock into tar – free syngas as well as higher thermal efficiency and low CO_2 emissions [NETL, 2012].

Its disadvantages include large initial costs relative to current landfills, highly corrosive plasma flame which may lead to frequent maintenance and component replacement with associated facility downtime. Requires large electrical energy input if the waste stream does not contain large fractions of unoxidized hydrocarbons.

Because biomass materials differ greatly in chemical, physical and morphological properties, their gasification methods are also different and consequently require different reactor design or even gasification technologies. Each type of gasifier will operate satisfactorily with respect to stability, gas quality and efficiency and pressure losses only within certain ranges of the fuel properties [FAO Corporate Document Repository, 1986].

Before choosing a gasifier for any biomass material it is important to ensure that the biomass meets the requirements of the gasifier or that it can be treated to meet these requirements. Practical tests are needed if the fuel has not previously been successfully gasified [FAO Corporate Document Repository, 1986].

The choice of one type of gasifier over the other is dictated by the fuel, its final available form, its size, moisture content and ash content [FAO forestry paper, 1986]. The advantages and disadvantages generally found for various classes of gasifiers are as shown in table 2.7.

Table 2.7 presents the advantages and disadvantages of various types of gasifiers.

Table 2.7 Advantages and Disadvantages of various Gasifiers [Rajvanshi, 1986].

Sr.No.	Gasifier Type	Advantages	Disadvantages
1.	Updraft	- Small pressure drop - Good thermal efficiency - Little tendency towards slag formation	- Great sensitivity to tar and moisture content of fuel - Relatively long time required for start up of IC engines - Poor reaction capability with heavy gas load
2.	Downdraft	- Flexible adaptation of gas production to load - Low sensitivity to charcoal dust and tar content of fuel	- Design tends to be tall - Not feasible for very small particle size of fuel
3.	Crossdraft	- Short design height - Very fast response time to load - Flexible gas production	- Very high sensitivity to slag formation - High pressure drop

2.6 Properties of syngas

The syngas produced differs from natural gas in terms of heating value (4 – 6 MJ/kg or 250 – 300 btu/scf and 18 – 27 MJ/kg or 1000 btu/scf for syngas and natural gas respectively), composition and flammability characteristics [NETL, 2012].

In terms of heating value and considering the application of syngas in gas turbines. The gas turbine requires a specified heat input to maintain performance, so a significantly higher flow rate is required for syngas than natural gas for a similar gas turbine. In terms of composition, natural gas consists mainly of CH_4 whereas syngas consists mainly of CO, H_2, CH_4, CO_2, N_2 and H_2O. However, the major combustible constituents of the syngas are CO and H_2. Figure 2.12 shows the percentage composition of the combustible and non – combustible constituents of the syngas.

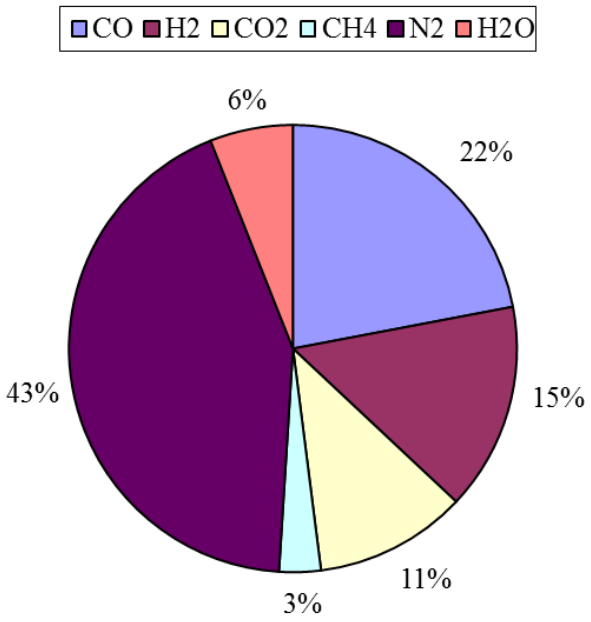

Figure 2.12 The composition of syngas

In terms of flammability characteristics, the hydrogen composition of syngas results in a higher flame speed and broader flammability limits, meaning the syngas produces a stable flame at leaner conditions than natural gas and combustion speed is much quicker than natural gas. In terms of contaminants is the relatively high concentration of H_2S in syngas compared to natural gas [NETL, 2012].

The syngas produced is affected by various processes as outlined above, hence variations in the gas produced can be expected from various biomass sources. The compositions of gas produced from various sources are listed in table 2.8. It has been established that the composition of the gas is a function of gasifier design and that, as such different calorific values may be given by the same fuel when used in two different gasifiers [Rajvanshi, 1986]. The maximum dilution of gas takes place because of the presence of nitrogen.

Almost 50-60% of gas is composed of noncombustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. However the cost and availability of oxygen may be a limiting factor in this regard.

Table 2.8 Composition of syngas from various fuels [Rajvanshi, 1986].

Fuel	Gasification method	Volume Percentage					Calorific value MJ/m^3	Ref.
		CO	H_2	CH_4	CO_2	N_2		
Charcoal	Downdraft	28-31	5-10	1-2	1-2	55-60	4.60-5.60	12
Wood with 12-20% moisture content	Downdraft	17-22	16-20	2-3	10-15	55-50	5.00-5.86	12
Wheat straw pellets	Downdraft	14-17	17-19	-	11-14	-	4.50	15
Coconut husks	Downdraft	16-20	17-19.5	-	10-15	-	5.80	15
Coconut shells	Downdraft	19-24	10-15	-	11-15	-	7.20	15
Pressed sugarcane	downdraft	15-18	15-18	-	12-14	-	5.30	15
Charcoal	Updraft	30	19.7	-	3.6	46	5.98	16
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29	17
Rice hulls pelleted	Downdraft	16.1	9.6	0.9	-	-	3.25	17

2.6.1 Advantages of biomass gasification

Biomass gasification is advantageous from a chemical and material handling point of view because the chemical composition and the choice of gasifier and gasifier operating parameters as well as the upstream processing of the biomass decide the product gas composition and quality [Brar *et al*., 2012]. The main advantages of biomass gasification include clean combustion, compact burning equipment, high thermal efficiency, a good degree of control, provides energy security, generates local employment in rural sector. In locations where biomass is already available at reasonably low prices (e.g. rice mill) or in industries using fuel wood, gasifier systems offer definite economic advantages. Biomass gasification technology is also environment-friendly, because of the firewood savings and reduction in CO_2 emissions [www.biozio.com].

2.6.2 Disadvantages of biomass gasification

The disadvantages of biomass gasification include the fact that it is quite complex, fuel is bulky and frequent fuelling is often required for continuous running of the system, handling residues such as ash, tarry condensates is a time consuming and dirty work and getting the syngas is not difficult, but obtaining the proper state is the challenging task [www.biozio.com].

2.6.3 The gasification of sugarcane bagasse

Biomass materials such as sugarcane bagasse are complex and contains several components which makes them more desirable to use as an energy resource. To develop an effective gasification process for bagasse, in particular for use as a high – quality

energy resource, for energy production in the form of electricity is of utmost importance [Osada *et al*., 2012].

After the extraction of the juice in the sugarcane plant, bagasse is left with over 50% moisture which makes gasification operations quite difficult [Boukis *et al*., 2004]. For classical gasification operation the bagasse has to be dried, which is an energy and time consuming step.

The gasification of sugarcane bagasse have been performed by previous researchers in various steps. The gasification of sugarcane bagasse on activated – carbon and titanium – supported ruthenium (Ru/C and Ru/TiO_2) catalysts in supercritical water was studied by Osada *et al*., and their results showed that bagasse was completely gasified to a mixture of gases (CO, H_2, CH_4) at specific conditions. Mohammadali *et al*., 2012 also investigated the feasibility of hydrogen production from the gasification of sugarcane bagasse at low temperature and in the presence of a catalyst. They found the influence of reaction time on gas yield and composition as well as on carbon gasification efficiency insignificant. They further extended the reaction time up to 4 hours which could not cause an attractive conversion of the bagasse and concluded that gasification efficiency would only be possible if temperature, pressure and reaction time are increased.

2.6.4 Gasification efficiency

System performance is measured in terms of its ability to convert the energy in the delivered feedstock into power.

An important factor determining the actual technical operation, as well as the economic feasibility of using a gasifier system is the gasification efficiency. Depending on the application of the gas, a useful definition of the gasification efficiency if the gas is to be used for engine applications is given by the expression:

$$\eta_m = \frac{(H_g \times Q_g)}{H_s \times M_s} \times 100\% \tag{10}$$

where:

η_m = gasification efficiency (%) (Mechanical)

Hg = heating value of the gas (KJ/m3)

Qg = Volume flow of gas (m3/s)

Hs = lower heating value of gasifier fuel (KJ/kg)

Ms = gasifier solid fuel consumption (kg/s)

If the gas is to be used for direct burning, gasification efficiency is sometimes defined as:

$$\eta_{th} = \frac{(H_g \times Q_g) + (Q_g \times \rho_g \times C_p \times \Delta T)}{H_s \times M_s} \times 100\% \tag{11}$$

where:

η_{th} = gasification efficiency (%) (Thermal)

Pg = density of the gas (kg/m3)

Cp = specific heat of the gas (KJ/kg°K)

ΔT = temperature difference between the gas at the burner inlet and the fuel entering the gasifier (°K).

In the case of mechanical applications, depending on the type and design of the gasifier as well as on the fuel characteristics, gasification efficiency may vary between 60 and 75%. But in the case of thermal applications, the value of the gasification efficiency can be as high as 93%.

South Africa has a gasification plant that uses sugarcane bagasse to produce electricity. This plant not only made enough electricity for the production of sugar from cane, but also produced electricity that is fed into the country's grid system.

Figure 2.13 shows a flow chat of the process of gasification.

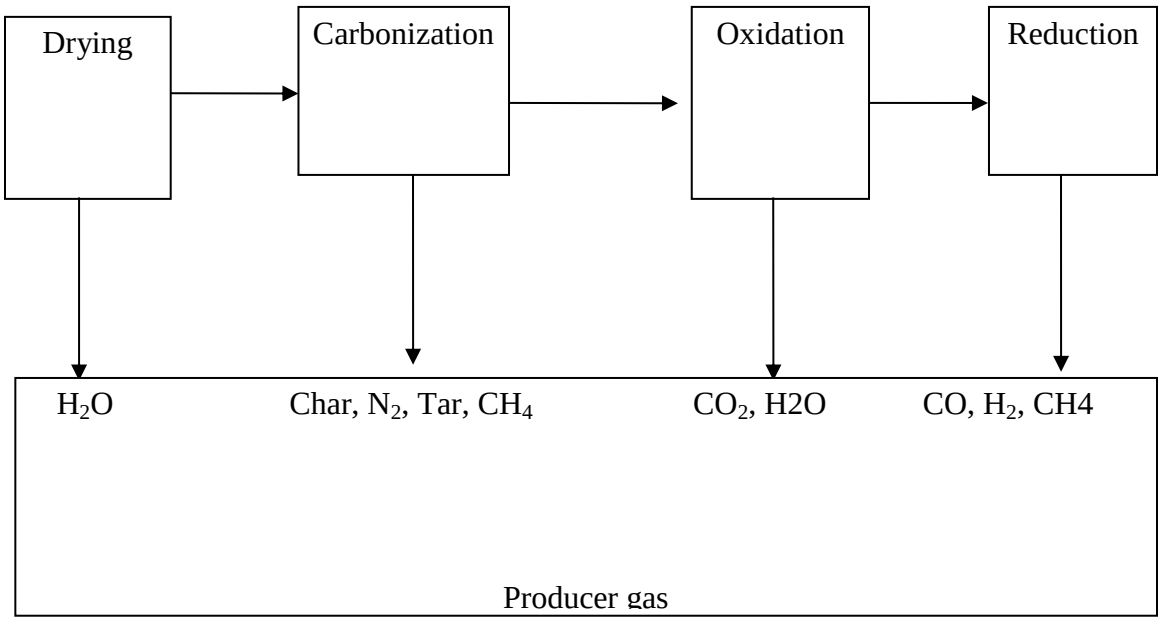

Figure 2.13 Summary of Gasification Process [Mamphweli, 2010].

Steam gasification of sugarcane bagasse with a semi batch reactor at steam temperatures of 800, 900 and 1000°C has been investigated and conclusions were drawn thus: [Ahmed and Gupta, 2012].

i. Evidence of fragmentation, secondary ring opening reactions and tertiary reactions that result in the formation of gaseous hydrocarbons was supported by higher flow rates of syngas and hydrogen at higher heating rates offered at high reactor temperature.
ii. Increase in carbon monoxide flow rate at the expense of carbon dioxide flow was observed.
iii. In the 1000°C run, a total merging (attributed to acceleration of char gasification reactions as well as the acceleration of steam hydrocarbon reforming reactions which are precursors to char formation by aromatization and repolymerization) between the pyrolysis step and the char gasification step was also observed.
iv. An increase in reactor temperature resulted in an increase in energy yield and apparent thermal efficiency.

A simplified model for the gasification process of sugarcane bagasse based on chemical equilibrium considerations of the Gibb's free energy of the gas produced was also investigated [Pellegrini and Oliveira Jr., 2007]. Moisture was identified as the main problem related to sugarcane bagasse gasification. It contributed to an increase in the destruction of exergy inside the reactor, as a result of an increase of the energy required

to evaporate the moisture. Therefore, the sugarcane bagasse must be dried to, at least, 30% moisture in order to start – up gasification according to equilibrium considerations. In order to evaluate performance and integration of Biomass Integrated Gasification Combined Cycle system (BIGCC) with process plants such as sugarcane mills, the study of the influence of low calorific gas operation on commercial gas turbines is necessary. [Pellegrini and Oliveira Jr., 2007].

2.7 THE SUGARCANE INDUSTRY IN SOUTH AFRICA

The South African sugar industry makes an important contribution to the national economy, generating in the region of R8 billion annual direct incomes. The industry also provides significant employment opportunities, particularly in rural areas. The industry produces an estimated average of 2.5 million tons of sugar per season with a total of 2 273 499 tons produced in 2007/08 of which 1 399 657 tons was for the national market and 873 842 for the international market. About 60% of this sugar is marketed in the Southern African Customs Union (SACU). The remainder is exported to markets in Africa, Asia and the Middle East [www.mbendi.com, 2012].

There are in the region of 42,300 registered sugarcane growers in South Africa. As mentioned earlier, most farming takes place in Kwazulu-Natal, with some farms in Mpumalanga and the Eastern Cape. There are six milling companies that make up the SA Sugar Millers Association Limited (SASMAL) and between them are operated 14 sugar mills and a central refinery. Five mills are owned by Illovo Sugar Ltd; four mills plus the central refinery are owned by Tongaat-Hulett Sugar Ltd; two mills by Tsb Sugar RSA Ltd; and one mill each by UCL Company Ltd, Umfolozi Sugar Mill (Pty) Ltd and

Ushukela Milling (Pty) Ltd. The forerunner of SASMAL, The Natal Sugar Millers' Association, is the founding father of the Sugar Milling Research Institute.

Three companies active in South Africa are Tongaat Hulett, Illovo and TSB. A brief overview of these companies have been provided.

Tongaat Hulett Sugar, started in 1854, is a world leader in sugar milling technology throughout the Southern African region. It has four mills in South Africa (Maidstone, Darnall, Amatikulu and Felixton) as well as central refinery, situated in Durban, which has an annual refining capacity of some 600, 000 tons [Hulett, 2012].

Illovo Sugar is Africa's biggest sugar producer with extensive agricultural and manufacturing operations in six African countries. These countries are South Africa, Tanzania, Malawi, Mozambique, Swaziland and Zambia. Illovo has a 38% share of industry production in South Africa and is a major supplier of sugar to African consumer and industrial markets [www.mbendi.com, 2012].

TSB Sugar, a wholly owned subsidiary of Remgro, has as its core business activity the production of refined and raw sugar that is marketed either nationally, by Quality Sugar under the Selati brand name, or exported through the South African Sugar Association (SASA) [www.mbendi.com, 2012].

The South African sugar industry makes an important contribution to the national economy, given its agricultural and industrial investments, foreign exchange earnings, its high employment, and its linkages with major suppliers, support industries and customers [Huletts, 2012].

Based on revenue generated through sugar sales in the SACU region as well as world market exports, the South African Sugar Industry generates an annual estimated average direct income of R8 billion. This constitutes R5.1 billion in value of sugarcane production [Huletts, 2012].

In terms of employment, the sugar industry provides direct employment in cane production processing, and indirect employment in numerous support industries in the three provinces where sugarcane is grown and processed, namely Kwazulu-Natal, Mpumalanga and the Eastern Cape. Direct employment within the sugar industry is approximately 77,000 jobs, which represents a significant percentage of the total agricultural workforce in South Africa. Indirect employment is estimated at 350,000. In addition there are approximately 35,300 registered cane growers. Approximately one million people, more than 2% of South Africa's population, depend on the sugar industry for a living [SASA, 2012].

In addition to initiatives undertaken as an industry, the South African Cane Growers' Association (SACGA) and the sugar milling companies undertake development projects and are involved in Broad-based Black Economic Empowerment (BBBEE) through a range of important initiatives [Mnisi and Dlamini, 2012].

The South African Sugar Industry (SASI) has also long recognized the need to promote diverse ownership of agricultural land under sugarcane and have a range of support instruments in place to promote the sustainability of such initiatives. As a result, 19% of freehold land under sugarcane has already been transferred to black growers. In order to progress the industry's target of 30% black ownership of freehold sugarcane land by

2014, the industry established in 2004 an independent land reform entity, called Inkezo Land Company. Inkezo's primary objective is to streamline transfer of ownership by identifying sellers and buyers, streamlining processes of land reform and promoting the sustainability of new ventures through outsourced support service providers or partners. Inkezo has facilitated the transfer of land previously owned by white farmers to more than 1,300 black growers [Huletts, 2012].

Companies and organizations linked to sugarcane farming in South Africa include: Bee-yomoba SPV (Pty) Ltd, Crookes Brothers Ltd, Illovo Sugar Ltd, Tongaat Hulett Ltd, UCL Company Limited, Inkezo Land Company, which is an independent land reform entity established by the South African Sugar Industry in order to progress the industry's target of 30% black ownership of freehold sugarcane land by 2014 [Sugar Beet SA, 2011].

A summary of the total crop of sugarcane as given by the South African Sugar Industry Directory of the 2007/2008 season for the past 7 years [SASA, 2009] is presented in table 2.9.

Table 2.9 Sugarcane production in South Africa [Garcia – Perez *et al*., 2002; Drummond *et al*., 1996].

Season	Million tons cane crushed	Dry bagasse produced*
2001/2002	21.16	5.71
2002/2003	23.01	6.21
2003/2004	20.42	5.51
2004/2005	19.09	5.16
2005/2006	21.05	5.68
2006/2007	20.28	5.48
2007/2008	19.72	5.33

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter presents the various methods employed in the characterization of sugarcane bagasse in order to determine its suitability for gasification as well as the thermal degradation analysis and gasification simulation employed.

Wet samples of sugarcane bagasse (~ 50wt% moisture) were obtained from TSB sugar, South Africa and were preserved to prevent contamination. The sugarcane bagasse was air – dried outdoors at ambient temperature of about 30°C for 14 days to lower the moisture content. The reason for pre – drying before analysis was to lower the moisture content of the material because high moisture content is undesirable during gasification as it will require more energy for gasification and will reduce the inside temperature of the gasifier as well as the heating value of the product gas [Mamphweli, 2009]. The dried sugarcane bagasse was ground to size range of 100μm and 20μm using a cryogenic grinder and was preserved in a sample container for analysis to be carried out.

3.2 PROXIMATE ANALYSIS

Proximate analysis gives the volatile matter and amount of fixed carbon present in sugarcane bagasse as well as moisture and ash contents. These properties were determined from the thermo gravimetric curve in figure 4.2 and were used during computer simulation of the gasification process.

3.3 ULTIMATE ANALYSIS

Ultimate analysis deals with the elemental composition of sugarcane bagasse. Knowledge of the elemental composition of biomass is important in order to estimate its energy output or its heating performance in conversion processes [Malatji, 2009]. The carbon, hydrogen, nitrogen and sulfur (CHNS) analyzer was used for ultimate analysis determination, which gave the elemental composition of the material in terms of the weight fractions of carbon, hydrogen, nitrogen and sulfur. Oxygen composition was determined by difference.

10 mg of the sample was weighed and mixed with an oxidizer (oxygen) in a tin capsule, which was then combusted in a reactor at 1000°C. The sample and container melted, and the tin promotes a violent reaction (flash combustion) in a temporarily enriched oxygen atmosphere. The combustion products CO_2, SO_2, and NO_2 are carried by a constant flow of carrier gas (helium) that passes through a glass column packed with an oxidation catalyst of tungsten trioxide (WO_3) and a copper reducer, both kept at 1000°C. At this temperature, the nitrogen oxide is reduced to N_2. The N_2, CO_2, and SO_2 were then transported by the helium to, and separated by a 2-m-long packed column and quantified with a thermal conductivity detector (TCD) set at 290°C. The chromatographic responses were calibrated against preanalyzed standards, and the CHNS elemental contents were reported in weight percentage. These elemental contents were also used during computer simulation of the gasification process.

3.4 FOURIER TRANSFORM INFRARED SPECTROSCOPIC (FT-IR) ANALYSIS

Biomass materials are constituted mainly of cellulose, hemicellulose and lignin with structural variability that is bound by functional groups. These functional groups are the chemically reactive groups of atoms within an organic molecule. They give organic molecules distinctive chemical properties because they are the parts involved in chemical reactions. However, the structures of these components are complex, as such; there is a need to understand these structures. The Fourier Transform Infrared Spectroscopy is a very useful tool to obtain information about the structure of the components of materials and the chemical changes taking place in these structures should there be any form of chemical pretreatment prior to gasification. It has been used in this project to characterize and estimate the carbohydrate content of sugarcane bagasse.

With reference to the structures of cellulose, hemicellulose and lignin in figures 2.1, 2.2 and 2.3 (a) and (b) in chapter 2, based on literature, the functional group present in both cellulose and hemicellulose is the acetal [$RC(H)(OR')_2$] group. Where R and R' are organic fragments. In the lignin structure the functional groups are the carbonyl (C═O) groups, the hydroxyl (-OH) groups and the methoxyl ($O-CH_3$) groups. The FT – IR analysis of sugarcane bagasse will further confirm these structures based on the functional groups present in the three major constituents.

The sugarcane bagasse sample was uniformly pressed with potassium bromide (KBr) pellets for the FT – IR analysis in transmission mode using the Perkin Elmer 2000 system

and spectra recorded over the range of 400 – 4000 cm^{-1} with a spectra resolution of 2 cm^{-1}. KBr is inert. It does not react with the sample to be analyzed and helps in better resolution of the peaks as it does not show absorbance in the infrared region which is why it is pressed with the sample to be analyzed under FT – IR.

3.5 THERMOGRAVIMETRIC ANALYSIS

The standard method of measuring the thermal degradation of a sample is through the thermogravimetric analysis where a small sample of the material, usually 5 – 15 mg in weight of the sample, is heated at a controlled rate in a controlled atmosphere while simultaneously recording weight, time and temperature. The thermogram that results has a characteristic shape for biomass [Jenkins *et al*., 1998].

An SDTQ 600 thermogravimetric analyzer was used to study the thermal behaviour of sugarcane bagasse. A 11.22 mg of the sample was heated at temperatures ranging from 20ºC – 1100ºC in three heating rates of 10°C/min, 15°C/min and 20°C/min in a nitrogen atmosphere under well – controlled laboratory conditions. Nitrogen was used to ensure an inert atmosphere so as to prevent the sample from oxidizing. It serves as an inert replacement for air where oxidation is undesirable. Three heating rates were used because results were analyzed using the model – free non isothermal thermo gravimetric analysis which requires a set of experimental tests at different heating rates. The operating conditions of the TGA are presented in table 3.1.

Table 3.1 TGA operating conditions.

Sample initial weight (mg)	11.122
Heating rate (ºC/min)	10, 15, 20
Heating Temperature (ºC)	20 - 1100

Starting from room temperature (20ºC), the sample was observed to dry since it contained moisture. Biomass being hygroscopic, extreme care is usually needed in handling to achieve a bone dry sample in the thermogravimetric (TGA) instrument. The data from the thermo gravimetric instrument was collected by a computer and the weight loss process observed as a function of temperature and time.

3.5.1 Derivative thermogravimetric analysis

The degree of thermal degradation was estimated by the use of the Derivative thermogravimetric analysis (DTG). It was applied in order to identify the exact temperature where a peak occurs. It was also applied to the thermo gravimetric analysis (TGA) data to determine the rate of weight loss as a function of temperature. The data obtained from both the thermogravimetric analysis (TGA) and its derivative (DTG), were used to obtain the kinetic parameters which were also used to model the devolatilization behaviour of the material.

3.5.2 Kinetic theory

The kinetic analysis provides information about the reaction order, the pre – exponential factor and the activation energy at different heating rates. However, it focuses on the temperature range where devolatilization mainly occurs.

The solid – state kinetic reaction is described by the following equation [Slopiecka *et al*., 2011]:

$$\frac{d\alpha}{dt} = k(T) f(\alpha) \tag{12}$$

The normalized form of the weight loss data of a devolatilized sample is the conversion rate, denoted α and is defined as:

$$\alpha = \frac{w_i}{w_i} - \frac{w_a}{w_f} \tag{13}$$

where w_i is the initial weight of sample w_a is the actual weight of the sample and w_f is the final weight of the sample.

It was assumed that rate constant, k, changes with absolute temperature according to the following Arrhenius equation:

$$\mathrm{K} = \mathrm{A}e^{-}\frac{E_a}{RT} \tag{14}$$

where E_a is the activation energy in kJ/mol, T is the absolute temperature (K), R is the gas constant (8.314 J $K^{-1}mol^{-1}$) and A is the pre – exponential factor (min^{-1}). Combining equations (12) and (14) gives the fundamental expression to calculate the kinetic parameters based on TGA results and is given as [Slopiecka *et al*., 2011]:

$$\frac{d\alpha}{dt} = \mathrm{A} \cdot f(\alpha) \cdot e^{-} \frac{E_a}{RT} \tag{15}$$

The function, $f(\alpha)$ and its derivative $f'(\alpha) = -1$ are used to describe solid – state first order reaction, hence the mathematical function $f(\alpha)$ are restricted by some authors to the following expression:

$$f(\alpha) = (1-\alpha)^n \tag{16}$$

where n is the order of reaction. Substituting equation (16) into equation (15) gives the reaction rate expression in the form:

$$\frac{d\alpha}{dt} = \mathrm{A} \cdot (1-\alpha)^n \cdot e^{-} \frac{E_a}{RT} \tag{17}$$

For non – isothermal TGA experiments at linear heating rate β = dT/dt, equation (17) can be written in a simplified form as follows:

$$\frac{d\alpha}{dt} = \frac{\mathrm{A}}{\beta} \cdot (1-\alpha)^n \cdot e^{-E_a/RT} \tag{18}$$

The fraction of the material consumed with time is expressed by equation (18).

One of the methods used to determine the kinetic parameters is the Model – free non – isothermal thermo gravimetric analysis which requires a set of experimental tests at different heating rates.

3.5.2.1 Kissinger Approach

The Model – free method used in this study is the Kissinger method of kinetic analysis which allows to determine the kinetic parameters of a solid – state reaction without known reaction mechanism.

A Model – free non – isothermal method developed by Kissinger was used to evaluate the kinetic parameters and the activation energy. This method does not require calculation of activation energy for each value of conversion in order to evaluate the kinetic parameters but allows the value of activation energy to be determined from a plot of ln (β/T^2_m) against $1000/T_m$ from a series of TGA experiments at different heating rates (β), where T_m is the maximum peak temperature of the DTG curve (presented in figure 4.4). The Kissinger equation is given by the following expression [Slopiecka *et al*., 2011]:

$$\ln\left(\frac{\beta}{T^2_m}\right) = \ln\left(\frac{AR}{E}\right) - \frac{E}{RT_m} \tag{19}$$

The activation energy E_a can be calculated from the slope of the plot, which is equal to – E_a/R. The pre – exponential factor is calculated from the intercept of the regression plot which is also equal to ln (AR/E_a) [Slopiecka *et al*., 2011].

3.6 HEATING VALUE

The heating value, sometimes called the calorific value, is the standard measure of the energy content of a fuel. The heating value of a substance, usually a fuel, is the amount of heat released during the combustion of a specified amount of that substance. It is usually measured by a formula (Dulong formula) giving the higher heating value of a material in terms of the weight fractions of carbon, hydrogen, oxygen, and sulfur from the ultimate analysis, or by the use of a calorimeter.

However, the heating value of a material cannot be measured directly, but only with respect to a reference state and the most widely used reference state is the higher heating value which uses water vapour as its reference state. The higher heating value is generally the most appropriate value to use for biomass combustors, although some studies may make use of the lower heating value instead, but this can lead to confusion [Ciolkosz, 2010]. Some biomass species can have more energy per unit of mass than others but variation between the species is often no greater than the natural variations found within one species or another. The heat content of a fuel type can vary significantly depending on the climate and soil in which the fuel was grown as well as other conditions [Ciolkosz, 2010]. As a result the energy content of a biomass should be thought of as a range rather than a fixed value. Fuel with high energy content is always better for gasification and most biomass has heating value in the range 10 – 16 MJ/kg [Chandrakant, 2002]. The heating value of sugarcane bagasse is approximately 20 MJ/kg [Basu, 2010].

Biomass feedstock has lower energy content than fossil fuels due to higher oxygen content [GCEP Energy Assessment Analysis, 2005]. Typical energy contents of biomass range from 0.5 to 17 MJ/kg depending on the biomass type. Conversion efficiency is based purely on energy in the feed [Maciejewska, 2006].

The heating value of sugarcane bagasse was determined by an oxygen bomb calorimeter (CAL2K Model). Figure 3.1 shows the oxygen bomb calorimeter used during measurement of the heating value of SB.

Figure 3.1 Oxygen Bomb Calorimeter

The Calorimeter was calibrated with 0.5g benzoic acid before measurements were taken. The heating value of the sugarcane bagasse was taken under a pressurized oxygen environment of 3 000 kpa.

3.7 SCANNING ELECTRON MICRSCOPE/ENERGY – DISPERSIVE X – RAY SPECTROSCOPIC ANALYSIS

Scanning electron microscope (SEM) was used for the morphological characterization of the material. The sample to be observed under SEM was mounted on conductive adhesive tape, sputter – coated with gold and observed under SEM using a voltage of 15 kV. The observations were undertaken at various magnifications as indicated in chapter 4.

The sugarcane bagasse with size 100μm was mounted on a specimen holder called a stub by a carbon double – sided tape. Before analysis with Scanning electron microscope (SEM) /Energy – dispersive X – ray spectroscopy (EDX), the sugarcane bagasse was coated with an ultra – thin coating of electrically – conducting material (Gold/Au) deposited on the sample by a device called the sputter coater. The reasons for coating were to increase conductivity so as to make microscopic viewing less complex as well as to protect and seal the sample to reduce the level of contamination. The sputter coater used was the Eiko IB3 Ion Coater. The sputter coater uses argon gas and a small electric field. The sugarcane bagasse was placed in a small chamber which is at vacuum. Argon gas was then introduced and an electric field was used to cause electrons to be removed from the argon atoms to make the atoms ions with a positive charge. The Argon ions were then attracted to a negatively charged piece of gold foil. The Argon ions act like

sand in a sandblaster, knocking gold atoms from the surface of the foil. These gold atoms then settled onto the surface of the sample, producing a gold coating.

After coating, the dimensional analysis of sugarcane bagasse was performed using the SEM MODEL JEOL (JSM – 6390LV). The sample was put in the sample chamber of the instrument for morphological viewing as well as identification of each element contained in the sample by EDX. To reduce errors and confirm the results, each analysis was repeated in triplicate under the same conditions and the content of each element was given as the average of these three replicates. Figure 1 presents the SEM of sugarcane bagasse.

3.8 GASIFICATION SIMULATION

A downdraft biomass gasification program developed by Jayah *et al*, 2003 was used to undertake computer simulation of the gasification of sugarcane bagasse. Table 3.2 shows the parameters used during simulations.

Table 3.2 Parameters used during gasification simulation.

Fuel properties	**Value**	**Gasifier operating conditions**	**Value**
Carbon (%)	44.1	Throat diameter (cm)	25.5
Hydrogen (%)	5.7	Throat angle (°)	30
Oxygen (%)	47.7	Insulation thickness (cm)	17.5
Nitrogen (%)	0.20	Thermal conductivity (W/cm K)	2.8
Fixed carbon (%)	18.19	Temperature of input air (K)	300
Bulk density (g/cm^3)	0.178	Air input (kg/hr)	44.5
Diameter of SB particle (cm)	14.3	Heat loss (%)	12.8
Moisture content	1.14 (%)		

The computer software was basically a model developed for the downdraft wood gasifiers to study the effects of operating and design parameters on the performance of the gasifier [Chen, 1986]. It consists of two sub-models, namely flaming pyrolysis and gasification zone sub-models. Flaming pyrolysis zone sub model is used to determine the product concentration and temperature of gas leaving the flaming pyrolysis zone. The gasification zone sub-model is used to predict the output of the product gas and the length of the gasification zone at any given time [Jayah, 2002]. The principle of mass and energy balance was also applied. Gas profiles were obtained during gasification simulation. The gas profiles obtained were used to calculate the gas heating value from the percentage composition of combustible gases in the syngas as follows [Mamphweli, 2009]:

$$HV_{gas} = \left(\frac{\left(CO_{vol} \times HVCO \right) + \left(H_{2vol} \times HVH_2 \right) + \left(CH_{4vol} \times HVCH_4 \right)}{100\%} \right) \quad (20)$$

where HV_{gas} is the gas heating value in MJ/kg, CO_{vol} is the volume concentration of carbon monoxide gas in percentage, $HVCO$ is the heating value of carbon monoxide gas (usually 12.64 MJ/kg by standard) [Bjerketvedt *et al*., 1997], H_{2vol} is the volume concentration of hydrogen gas in percentage, HVH_2 is the heating value of hydrogen gas (10.1 MJ/kg by standard) [Fossum and Beyer, 1998], CH_{4vol} is the volume concentration of methane gas in percentage, $HVCH_4$ is the heating value of methane gas (38 MJ/kg by standard measurement) [Bjerketvedt *et al*., 1997]. The heating values of the combustible gases were obtained from the standard gas table.

3.8.1 Flaming pyrolysis zone sub model

In the flaming pyrolysis zone, the general equation of the reaction of the material can be expressed by equation 21:

$$CH_aO_b + wH_2O + m(0.21O_2 + 0.79N_2) \rightarrow x_{char}Char + x_{tar}Tar + x_1CO + x_2H_2 + x_3CO_2 + x_5CH_4 + x_6N_2 \quad (21)$$

where char was taken as carbon and ultimate analysis of tar as $CH_{1.03}O_{0.03}$ [Adams, 1980]. From equation 22 and 23 we can obtain the equilibrium equation and the corresponding equilibrium constant respectively.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (22)$$

$$K_3 = \frac{x_3 \times x_2}{x_1 \times x_4} \quad (23)$$

The correlation between the temperature and equilibrium constants for the above is given by equation 24 [Gumz, 1950].

$$Log(K_3) = -36.72508 + \frac{3994.704}{T} - 4.46241 \times 10^{-3}T + 6.71814 \times 10^{-7}T^2 + 12.2228\log(T) \quad (24)$$

where T is the temperature in Kelvin.

By mass balance the following equations 25 – 28 can be obtained:

Carbon: $$1 = x_{char} + x_{tar} + x_1 + x_3 + x_5 \quad (25)$$

Hydrogen: $$a + 2w = 1.03x_{tar} + 2x_2 + x_1 + 2x_4 + 4x_5 \quad (26)$$

Oxygen: $$b + w + 0.42m = 0.03x_{tar} + x_1 + 2x_3 + x_4 \quad (27)$$

Nitrogen: $$0.79m = x_6 \quad (28)$$

The energy balance in flaming pyrolysis zone is given by equation 29:

$$H_c wood = H_c Char + H_c Tar + H_c Gas + H_s Char + H_s Tar + H_s Gas + Heatloss \quad (29)$$

The number of moles of water *(w)*, including fuel moisture, air moisture, and water or steam addition can be calculated by the following relationship [Chen, 1987]:

Moisture in fuel = dry matter in fuel × moisture content on dry basis

$$w = (12 \times 1 + 1 \times a + 16 \times b) \times mc_{db} kg \quad (30)$$

The values of a and b have been given. Heat loss and *m* (number of moles of oxygen input) are obtained from the experiment, x_5, x_{char} and x_{tar} are assumed, x_1, x_2, x_3, x_4, x_6 and T are solved by using the successive approximation method with a Fortran program. The higher heating value (MJ/kg) of bagasse, char and tar are calculated from the equation as follows (Gaur and Reed, 1998).

$H_C Wood = 0.3491 f_C + 0.1783 f_H - 0.1034 f_O$ (N_2 and ash content are neglected) (31)

$$H_C Char = 0.3491 \times f_{C,char} \quad (32)$$

$$H_C Tar = 0.3491 \times f_{C,tar} + 0.1783 f_{H,tar} - 0.1034 f_{O,tar} \quad (33)$$

The chemical energy content of output gas, and sensible energy of char, tar and output gases are calculated as follows:

$$H_C Gas = 241000x_1 + 283000x_2 - 802300x_5 \quad (34)$$

$$H_S Char = 12.15x_{char} \times (T - 300) \quad (35)$$

$$H_S Tar = 21.95x_{tar} \times (T - 300) \quad (36)$$

$$H_S Gas = x_1 H_{CO} + x_2 H_{H2} + x_3 H_{CO2} + x_4 H_{CO2} + x_4 H_{H2O} + x_5 H_{CH4} + x_6 H_{N2} \quad (37)$$

3.8.2 Sub – model of gasification zone

The gasification zone is modelled by following a particle along the axis of the reactor. The computer program has been formulated using Fortran language to calculate the characteristic profiles along the reactor axis. The profile includes temperature, concentrations, efficiency and distance the particle travelled. The length co-ordinate is coupled with a time variable through the solid phase velocity. A small time increment approach is used in calculating the product composition of the zone. It involves the use of a step procedure starting from the gasification zone and marches axially through the reactor in appropriate time increments. The output values of the flaming pyrolysis zone are used as inputs for modelling the gasification zone [Jayah, 2002].

The conversion efficiency of the gasifier was determined after computer simulation of the gasification process by the following equation [Mamphweli, 2009]:

$$\eta = \left[\left(\frac{HV_{gas} \times 2}{HV_{fuel}} \right) \times 100\% \right] \quad (38)$$

where η is the efficiency of the gasifier, HV_{gas} is the gas heating value and HV_{fuel} is the heating value of the fuel (sugarcane bagasse). The 2 in the equation represents the gas flow rate in Nm^3/h from the gasifier.

During gasification simulation, the following gasifier operating parameters were varied: throat diameter and throat angle as well as the temperature of air input. These parameters are the most critical operating parameters that affect gasifier performance [Reed and Das, 1988]. The parameters were varied in order to establish conditions that would result in the highest possible conversion efficiency. Because moisture content is one major fuel property that governs gasifier design and conversion efficiency, the moisture content was also varied between 1.14%, 15% and 25% respectively. The first moisture value (1.14%) is as measured from the material while the other two values (15% and 25%) were assumed based on the maximum allowable moisture content in order to determine the impact of moisture content on the conversion efficiency of the gasification process.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the results obtained using the methods discussed in chapter 3. The results are presented and discussed in relation to existing theory and the objectives of the research. The need for the data presented and the methods employed in data collection are justified and used to answer the research questions presented in chapter 1.

4.2 PROXIMATE ANALYSIS

Table 4.1 presents the proximate analysis of sugarcane bagasse under study. This was obtained from the thermogravimetric curve in figure 4.2. The values correspond well with those reported in the literatures.

Table 4.1 Proximate analysis of Sugarcane bagasse (SB)

Components	**(%) Composition**
Moisture content	1.14
Volatile matter content	69.99
Fixed carbon	16.39
Ash	1.42

The low moisture content in sugarcane bagasse was due to the fact that the sample was air dried before the measurement was undertaken, thereby making it suitable for gasification operations. A low moisture level is usually preferred because high moisture fuels take time to ignite and provides less useful heat per unit mass [Ciolkosz, 2010]. For trouble free and economical operation of the gasifier, moisture content below 21% is desirable [Mamphweli, 2009]. During gasification, moisture is removed and converted into steam at temperatures below 100ºC.

Volatile matter content was reported to be high in the material as evident in table 4.1 which can be attributed to the material's organic nature. The high volatile matter content indicates a potential for creating large amounts of inorganic vapours during gasification [Jenkins *et al*., 1998]. Fuels with high volatile matter content tend to vapourize before combustion (flaming combustion) whereas fuels with low volatile matter content will burn primarily as glowing char and the performance of the combustion chamber is affected by this property and is usually taken into account when designing gasification systems for biomass [Ciolkosz, 2010]. Ash composition was also observed to be low in the sample as evident from table 4.1, which is typical of biomass materials [Surinder *et al*., 2003]. The low level of ash and the high volatile matter content makes the material suitable for gasification [Surinder *et al*., 2003]. On the other hand, low ash content is desirable for gasification to take place as high amount of ash could result in agglomeration and slagging as well as ash deposition, fouling and corrosion during gasification [Gustafsson, 2011]. At specific temperature (1200°C to 1600C°), depending on the composition of the ash, the ash starts to melt, thereby affecting the smooth running of the gasifier system [Chandrakant, 2002]. The ash content and its composition are

important factors for biomass use in thermochemical processing due to its catalytic activity [Bridgwater, 1995]. During gasification, ash can be collected after cooling and cleaning the syngas, and then recycled for further use in industrial processes. The sugarcane bagasse under study was found to meet the gasification requirements with regard to ash content measured to be 1.42% as presented in table 4.1.

4.3 ULTIMATE ANALYSIS

The ultimate analysis of SB is presented in table 4.2. A carbon, hydrogen, nitrogen and sulfur (CHNS) analyzer was used to undertake the elemental analysis. Oxygen was obtained by difference, which was calculated as 100% minus the sum of carbon, hydrogen, and nitrogen and sulfur as obtained from the CHNS analyzer. The ratio of the products formed during gasification of biomass is influenced by the chemical composition of the biomass fuel and the operating conditions [Chandrakant, 2002].

Table 4.2 Ultimate analysis of sugarcane bagasse (SB)

Chemical Composition	**(%) Composition**
N	0.20
C	44.1
H	5.7
S	2.3
O	47.7

From table 4.2, it can be observed that sugarcane bagasse contains more oxygen than any other element in the table, which can be attributed to its carbohydrate structure. However, high oxygen content will reduce the energy density of the sample [Kumar *et al*., 2009].

During gasification oxygen is removed as it reacts with carbon and hydrogen to form CO_2 and H_2O as described by equation 4 and 5 in chapter 2. The CO_2 produced reacts with carbon to form carbon monoxide as described by equation 6 in chapter 2, and the H_2O reacts with carbon to produce CO and H_2 as indicated in equation 7 in chapter 2. Therefore the presence of oxygen is important to start the syngas formation process. Sugarcane bagasse gasification occurs under much less severe operating conditions when compared to the coal feedstock because, oxygen, which appears to be its main constituent has higher reactivity than the oxygen – deficient carbonaceous materials in coal [Jenkins *et al*., 1998]. Table 4.2 also shows that sugarcane bagasse is rich in carbon being the second highest element (44.1%) after oxygen in the table. The conversion of carbon in the material into carbon monoxide is the essence of gasification [Chandrakant, 2002]. Nitrogen composition of the material is relatively low as can be observed from the table. During gasification, the nitrogen content of the material results primarily in ammonia (NH_3) and high hydrogen cyanide (HCN). Ammonia, if not removed, the combustion of part of it (occurring at temperatures above 1000ºC, typically the temperature at which combustion takes place) will result in the formation of NO_X [Kumar *et al*., 2009]. On the other hand, HCN concentrations (300 mg/m^3) in air will kill a human within about 10 minutes [International Cyanide Management Institute, 2006]. However, the conversion of nitrogen to hydrogen cyanide is very low in biomass gasification unlike coal gasification [Goldschmidt, 2001]. Fuel with less than 2% nitrogen content is safe for gasification [Chandrakant, 2002]. Sulfur composition is also relatively low. During gasification, sulfur in the fuel is converted into hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). Because of the low sulfur content of the material, the syngas sulfur content is low enough

to meet the needs of most applications. The generation of H_2S is of little importance in gasification of sugarcane bagasse provided sulfur content does not exceed 5% [Chandrakant, 2002]. Hydrogen composition was also found to be low (5.7%).

Figure 4.1 presents the EDX analysis of sugarcane bagasse. A Scanning electron microscope/Energy Dispersive X – ray spectroscopic meter was used to undertake this analysis.

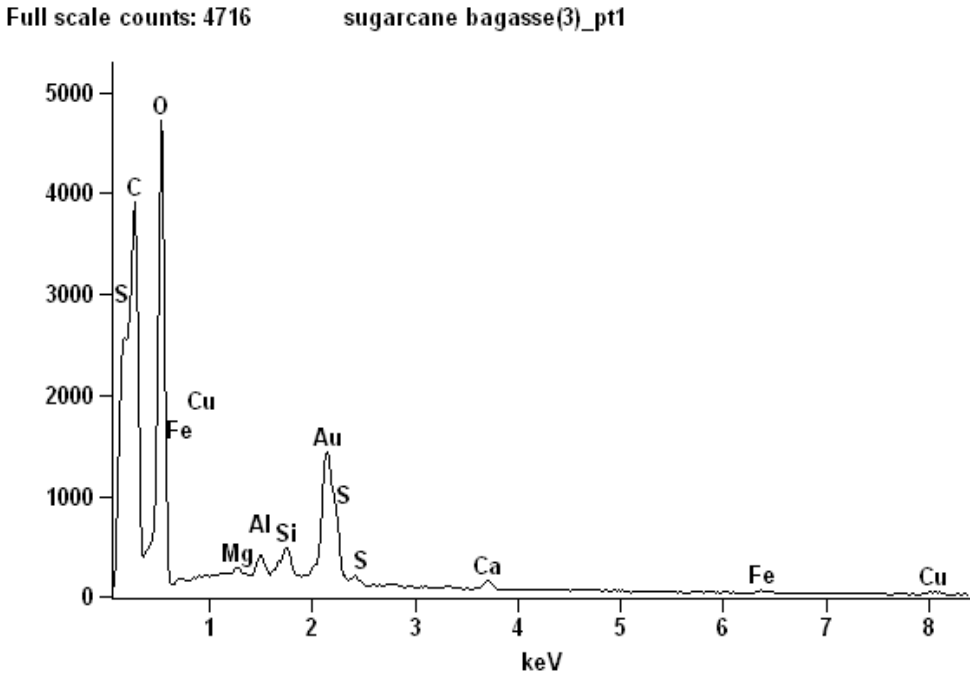

Figure 4.1 EDX spectrum of sugarcane bagasse (SB)

The EDX analysis also gave the elemental composition of the material. While the CHNS analyzer is restricted only to the analysis of carbon, hydrogen, nitrogen and sulfur, the EDX analyzes and gives the percentage of more elements than the CHNS analyzer with the exception of hydrogen. The EDX cannot detect hydrogen because of the low atomic number of hydrogen. However, it can only detect elements from carbon (atomic number

6) upwards. This implies that it cannot detect elements with atomic numbers 1 to 5, namely hydrogen (H_2) with atomic number 1, helium (He) with atomic number 2, lithium (Li) with atomic number 3, beryllium (Be) with atomic number 4 and boron (B) with atomic number 5.

It was found that the material comprised the elements, oxygen, carbon, sulfur, iron, copper, magnesium, calcium, silicon and gold in varying amounts. However, the fate of oxygen, carbon and sulfur content of the material in relation to gasification has previously been discussed in this chapter. The elements, silicon (Si), aluminium (Al), calcium (Ca), magnesium (Mg), Iron (Fe) and copper (Cu) are present in minute quantities. These elements partly volatilize during gasification at temperatures above 700ºC. Silicon, calcium and magnesium are the major ash – forming elements in the material while aluminium and iron are the minor ash – forming elements during gasification [Gustafsson, 2011]. Since gasification takes place in air or oxygen atmosphere, silicon (Si) in the material stream ends up as silica (SiO_2) (a compound composed of silicon and oxygen). High level of silica in the gasifier feed forms sintered or fused deposits as well as slagging and can cause operational problems. The temperature in the combustion zone of the downdraft gasifier is about 800 – 1500ºC or more. The melting point of silica is approximately 1400ºC or more depending on its composition [Elert, 2012]. During gasification, silica melts at a temperature above 1400ºC forming fused silica which may stick on the walls of the gasifier hampering the smooth operation of the gasifier. In order to prevent operational problems posed by high levels of silica, the level of silica must not exceed 9 – 10% [Jenkins, 1998]. Should the

level of silica, during gasification of sugarcane bagasse exceed the specified limit, an upstream processing of the bagasse may be necessary to make it suitable for gasification operations. However, silica level in the material under study is relatively low as evident from figure 4.1, which can be attributed to a number of factors including soil type (in particular, soil texture) where the sugarcane was grown, growing, handling and storage conditions as well as timing of harvest. This also explains why the sugarcane bagasse used for this study exhibited low ash content as evident in table 4.1.

The presence of the element gold (Au) can be attributed to the fact that gold was used as the coating material on the sample before the EDX analysis was undertaken in order to prevent contamination of the material and to increase conductivity so as to make microscopic viewing less complex.

4.4 FOURIER TRANSFORM INFRARED SPECTROSCOPIC (FT-IR) ANALYSIS

Figure 4.2 shows the FT – IR spectra of sugarcane bagasse. This is presented in order to estimate the carbohydrate structure of sugarcane bagasse.

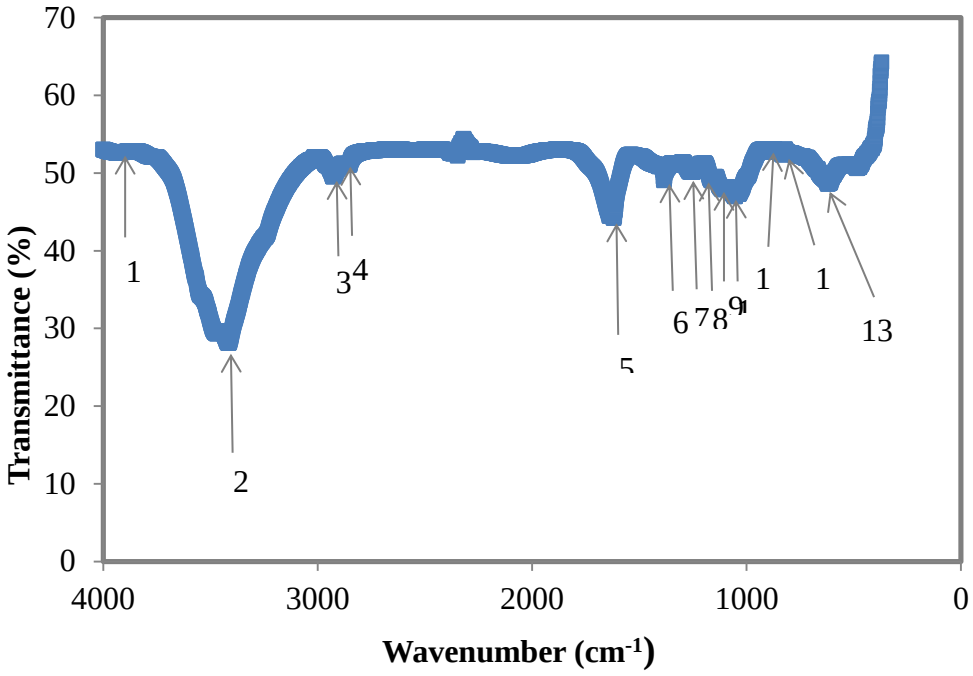

Figure 4.2 FTIR spectra of sugarcane bagasse

There are no structural/spectral changes to the material due to the fact that the material was not subjected to any chemical pretreatment prior to analysis. However, the FTIR spectra revealed the presence of oxygenated compounds in sugarcane bagasse. Due to the complexity of sugarcane bagasse, most of the spectral bands have contributions from the three major components (cellulose, hemicellulose and lignin).

As evident from figure 4.2, peak 1 and peak 2 corresponds to stretching O-H asymmetric around 3436 cm^{-1}. The stretching at peak 3 corresponds to the CH stretching in CH_3, and CH_2 at 2850 cm^{-1}, while peak 4 reveals the CH stretching in OCH_3 at 2800 cm^{-1}. Peak 5 reflects O-H and conjugated C-O at 1651 cm^{-1} while the aromatic skeletal vibration in lignin (C═C) is observed around 1389 cm^{-1} in peak 6. Peak 7 corresponds to C-H vibrations in cellulose and C-O vibrations in derivatives of syringyl at 1300 cm^{-1}. The guaiacyl ring breathing, C-O stretch in lignin and C-O linkage in guaiacyl aromatic

methoxy group is observed at 1180 cm^{-1} for peak 8 and C-O-C vibrations in cellulose and hemicellulose at 1133 cm^{-1} for peak 9 while peak 10 reflects C-H and C-O deformation observed at 1085 cm^{-1}. Aromatic skeletal and C-O stretch corresponding to peak 11 is observed at 934 cm^{-1} while peak 12 with intensity at 862 cm^{-1} is assigned to the C-H out-of-plane vibrations in lignin. The peak intensity at 658 cm^{-1} (peak 13) is assigned to C-H deformation in cellulose. The conversion of all these components in sugarcane bagasse as revealed by the FTIR into desired products is the essence of gasification [Chandrakant 2002].

During gasification, these components as contained in sugarcane bagasse play a major role in the syngas formation process as they are all disintegrated at elevated temperatures.

4.5 THERMOGRAVIMETRIC ANALYSIS

Figure 4.3 shows the thermogravimetric (TGA) plot for sugar cane bagasse under study. This was undertaken by use of a thermo gravimetric analyzer which was used to observe the weight loss of the sample as a function of temperature.

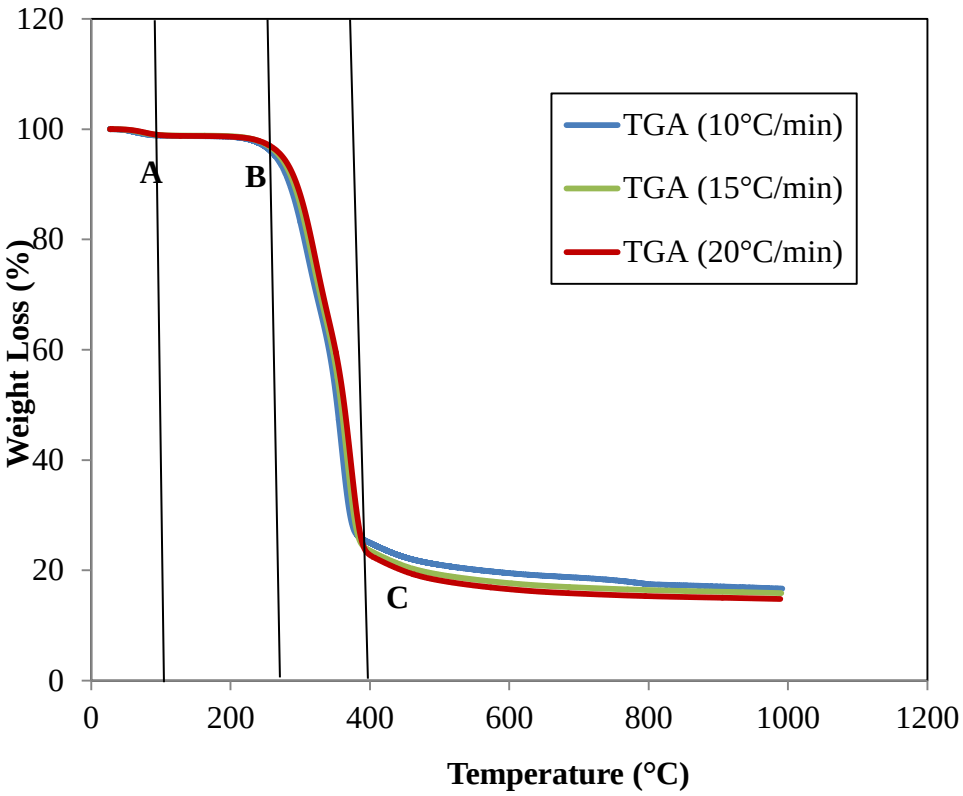

Figure 4.3 TGA curve of sugarcane bagasse

In general, three distinct weight loss stages could be noticed from figure 4.3, namely dehydration, active and passive weight loss stages. These have been labelled A, B and C. The dehydration weight loss stage reflects loss of water, the active weight loss stage reflects the decomposition of hemicellulose, cellulose and part of lignin as well as extractives, and the passive weight loss stage reflects slow and continuous lignin degradation. In the first region labelled A, as can be observed in figure 4.3, a reduction in weight at temperatures lower than 100°C is observed and can be attributed to loss of moisture from the material. From the second region labelled B, in the temperature range 100–260°C, the devolatilization of hemicellulose, cellulose and part of lignin as well as

extractives occur. Biomass materials are composed mainly of cellulose, hemicelluloses and lignin [Shafizadeh, 1982]. Stage B indicates weight loss mainly due to the decomposition of these components [Biagini *et al*., 2006]. The degradation of hemicellulose and part of cellulose begins around 210ºC continuing up to 350ºC [Surinder *et al*., 2003]. The degradation of the material in the temperature range 350 – 500ºC is due mainly to the decomposition of cellulose and lignin in the material. In stage C there is a much lower rate of weight loss than in stage B, which corresponds partly to the end of cellulose degradation and partly to the beginning of degradation of heavier volatiles and formation of char. Degradation of lignin also continues in this region (above 1000°C) [Kumar *et al*., 2008].

4.5.1 Derivative thermogravimetric analysis

Thermo gravimetric analysis was undertaken to establish the thermal stability and the gasification temperature of sugarcane bagasse. The Derivative thermogravimetric (DTG) plot for sugarcane bagasse at various heating rates is presented in figure 4.4. This was obtained from the TGA curve in figure 4.3. It was used to estimate the rate at which thermal degradation of sugarcane bagasse takes place at various heating rates over a wide temperature range (0 – 1000°C).

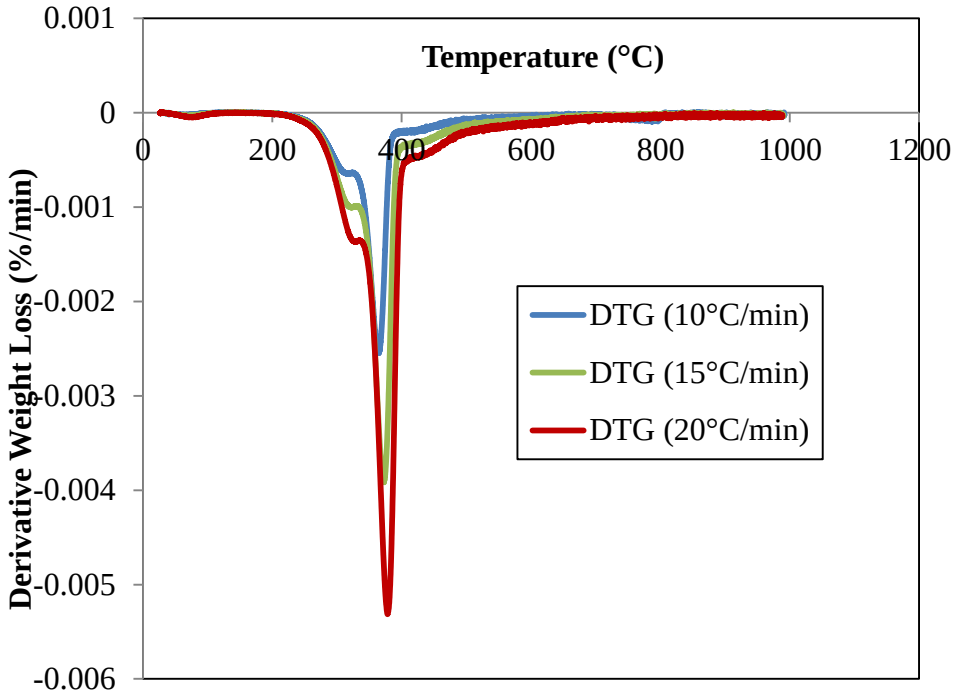

Figure 4.4 DTG curve of sugarcane bagasse at various heating rates (SB)

It can be observed from figure 4.4 that the positions of the peak are shifted to a lower temperature region as heating rate is increased. The exact temperature where maximum rate of devolatilization occurs is described by the position of the peaks. During devolatilization, two slightly distinct peaks could be noticed at 10ºC/min and 15ºC/min heating rates. This is caused by a change in the slope of the TG plot. At 20ºC/min heating rate, the DTG peaks are quite inconspicuous being much closer to each other and the maximum degradation of cellulose and hemicellulose peaks occurring at a much lower temperature. The cause of the merged DTG peaks can be attributed to the catalytic behavior of mineral matter present in the material [Antal and Varhegyi, 1995].

4.5.2 Kinetic analysis

The results obtained from the TGA were elucidated according to the model – free method to determine the kinetic parameters. The activation energy (E_a) and the pre – exponential factor (A) were obtained using the Kissinger method of kinetic analysis. These were calculated from equation (19) in chapter 3. The maximum peak temperatures were determined from figure 4.4. The plot of ln (β/T^2_m) against 1000/T K^{-1} of the devolatilization process for sugarcane bagasse is presented in figure 4.5. The equations of regression and the square of the correlation coefficient (R^2) are also presented. The activation energy (E_a) and the pre – exponential factor (A) were derived from the slope and intercept of the regression line plot.

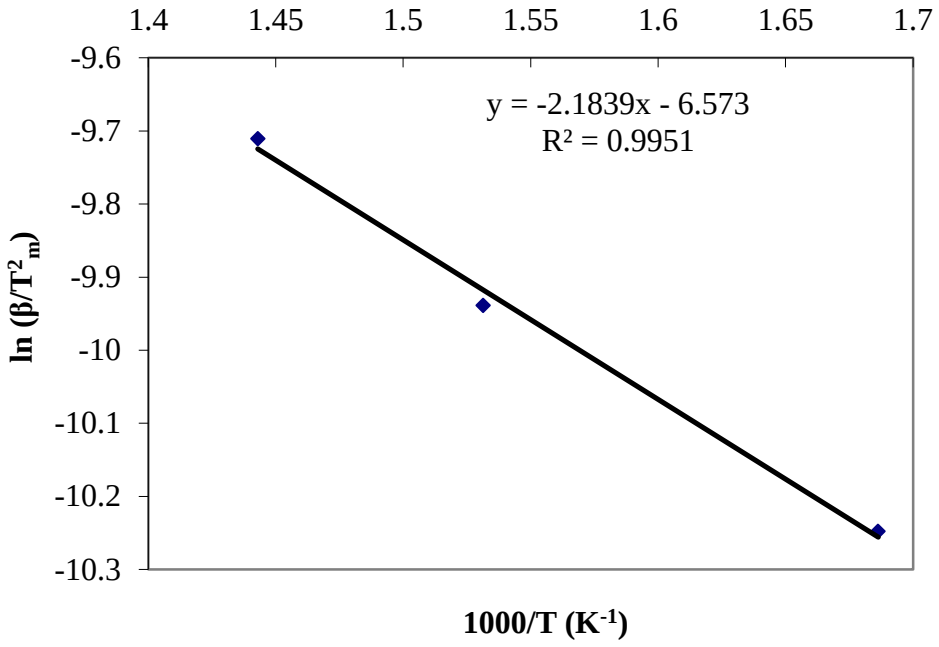

Figure 4.5 Determination of kinetic parameters for the decomposition of Sugarcane bagasse.

The activation energy and the pre – exponential factor were found to be 181.51 kJ/mol and 3.1×10^3/min respectively. These values of kinetic parameters are in good agreement with values in the literature and can be successfully used to understand the devolatilization mechanism of solid – state reaction. Aboyade *et al*., 2013, investigated the non – isothermal thermokinetics of sugarcane bagasse and found apparent activation energy value for sugarcane bagasse in the range 165 – 180 kJ/mol in the 0.1 – 0.8 conversion range. The thermal devolatilization of sugarcane bagasse in an inert atmosphere was also studied by Aboyade *et al*., 2011 and results showed that activation energy ranged from 170 – 225 kJ/mol in the 0.1 to 0.8 conversion range. Mamdouh, 1998 also studied the kinetics of bagasse and found its activation energy to be 33.4 kJ/mol. The value of activation energy is an indication of a chemically controlled common type of compensation effect of the kinetic parameters. Reasonably accurate values of the kinetic parameters are necessary in the design and development of thermochemical conversion systems for biomass.

During gasification the major part of the syngas is formed through reaction chemistry that are mostly endothermic reactions. Therefore, the value (181.51 KJ/mol) for activation energy reflects the amount of energy needed to start the reaction for the syngas formation. On the other hand, the pre – exponential factor represents the frequency of collisions between reactant molecules and it is in itself dependent on temperature because it is related to molecular collisions. From the collision theory of chemical reactions, molecules react if they collide with a relative kinetic energy along their lines – of – center that exceeds the activation energy. Thus the heat production as well as the rate at which

devolatilization products are carried away in the gasifier are dependent on the flow of gas and rate of particle collision which drives the biomass conversion to syngas [Pepiot *et al*., 2010]. Therefore, the value of pre – exponential factor (3.1×10^3/min) represents the frequency at which particles collide during gasification reaction because heat and mass balance inside the particles play a vital role in the conversion to syngas and needs to be taken into account when describing gasification processes [Pepiot *et al*., 2010].

4.6 HEATING VALUE

Table 4.2 presents the measure of the heating value of sugarcane bagasse from this study and from previous authors. The heating value was measured using an oxygen bomb calorimeter.

Table 4.3 Measure of the energy content of sugarcane bagasse from this study and from previous authors.

Fuel (Sugarcane bagasse)	**Energy content (MJ/kg)**
Present study	17.8
Stanmore, 2010	19
Jenkins *et al*., 1998	17.3 – 19.4

The measured heating value of the bagasse was used during computer simulation of the gasification process. The measured bagasse heating value is comparable to the ones found in the literature as evident from table 4.3. The heating value is an indication of the energy available for conversion to useful energy.

4.7 MORPHOLOGICAL CHARACTERIZATION

The micrographs of sugarcane bagasse are presented in figure 4.6. These were obtained after analysis under a scanning electron microscope.

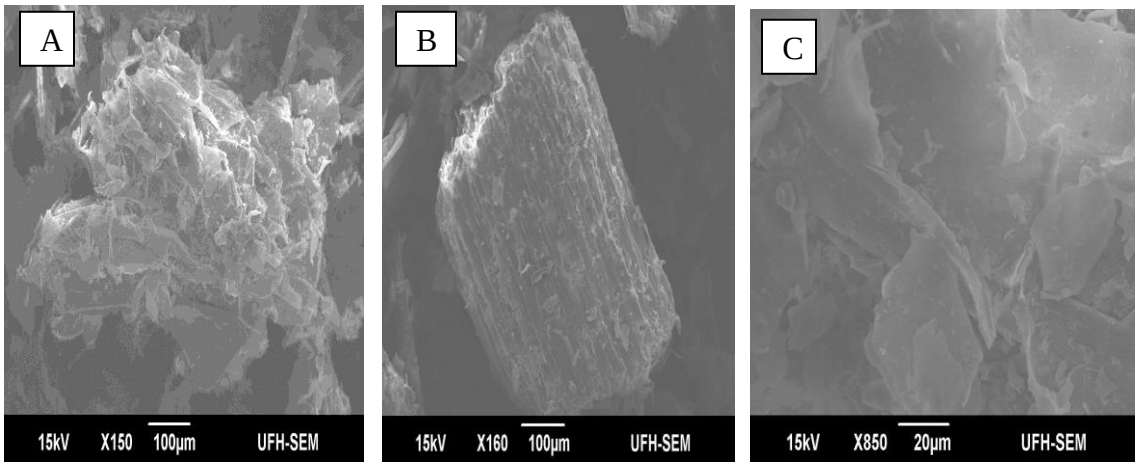

Figure 4.6 Scanning electron micrographs of sugarcane bagasse at 150x magnification (A), 160x magnification (B) and 850x magnification (C).

Figure 4.6 (A) is a general view of the material showing mainly the fibers while (B) and (C) are higher magnification images of fiber surface of the material. The micrographs clearly show the shape, size distribution and roughness of the surface of different parts of the material. A rigid and compact morphology of the material can also be noticed. It can also be observed that the material has a flattened shape. No morphological changes on the surface of the material were evident which can be attributed to the fact that the material was not subjected to any chemical pretreatment prior to analysis under SEM. However, the latter observations confirm that sugarcane bagasse is a carbonaceous material suitable for gasification through a downdraft gasifier properly designed to accommodate the

properties of the bagasse. This was also confirmed through the elemental analysis undertaken by the use of EDX and CHNS analyzer.

4.8 GASIFICATION SIMULATION

A computer simulation program developed by Jayah *et al*., 2003, described in chapter 3 was used to undertake computer simulation of the gasification of sugarcane bagasse used for this study. The initial parameters used are presented in table 3.2 in chapter 3. Some of the parameters were varied in order to investigate their impact on the conversion efficiency of the gasification process of sugarcane bagasse after computer simulation. The impact of moisture content on the product gas volume was also considered. The parameters that were varied are presented in table 4.4.

Table 4.4 Parameters varied during gasification simulation.

Parameter	**Range**
Moisture content (%)	1.14, 15, 25
Diameter of SB particle (cm)	6, 20, 30
Temperature of input air (°C)	27, 627, 1227
Throat diameter (cm)	10, 30, 50
Throat angle (º)	25, 40, 90

The varied fuel properties and parameters include moisture content, diameter of the sugarcane bagasse particle, temperature of input air and throat diameter as well as throat angle as evident in table 4.4. Figures were played around with based on assumption

before finally establishing those that led to maximum conversion efficiency as well as those that led to reduced conversion efficiency of the gasification process. Moisture content of 1.14% is as measured from the sample while 15% and 25% moisture contents were assumed based on maximum allowable moisture content. The impact of various fuel properties and gasifier operating conditions are described in the following sub – sections.

4.8.1 Impact of fuel moisture content on gas volume

The fuel properties and gasifier operating parameters presented in table 3.2 and 4.4 were used to undertake computer simulation with only moisture content varied from 1.14% to 15% and 25% respectively. Figure 4.7 shows the impact of moisture content on gas volume obtained during gasification simulation using the gasifier operating parameters presented in tables 3.2 and 4.4 respectively.

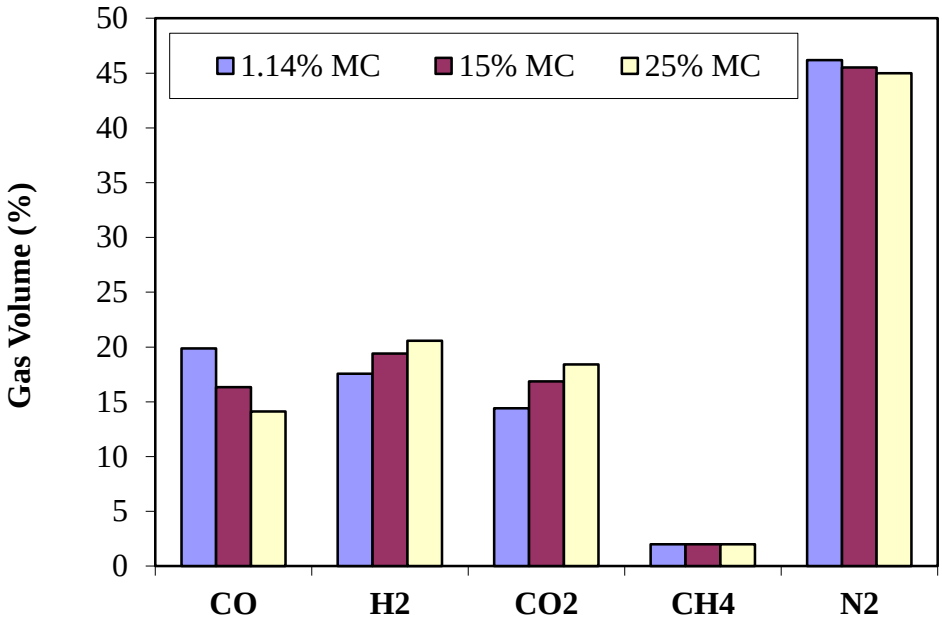

Figure 4.7 Gas volumes obtained through computer simulation

The major part of the syngas is formed through reduction reactions in the reduction zone of the gasifier most of which are endothermic reactions. The impact of moisture content on gas volume is evident from figure 4.7. The volume of carbon monoxide (CO) was found to be higher when the moisture content of the material was low (1.14%) compared to when it was higher (15% and 25% respectively). This can be attributed to the fact that a limited quantity of heat was consumed during the drying of the feedstock while most of the heat was rather available for the reduction reactions to take place. This means that at higher moisture content, more heat is required for drying leaving less energy available for the reduction reactions that produce CO. The hydrogen content was found to be higher when the moisture content of the material was assumed to be higher (15% and 25% respectively). This is because of the availability of moisture for the water – gas reaction to take place.

4.8.2 Impact of fuel moisture content on conversion efficiency

Figure 4.8 shows the impact of fuel moisture content on conversion efficiency. This was obtained after computer simulation of the gasification process using the parameters presented in table 3.2 and 4.4. The moisture content was varied between 1.14%, 15% and 25% respectively.

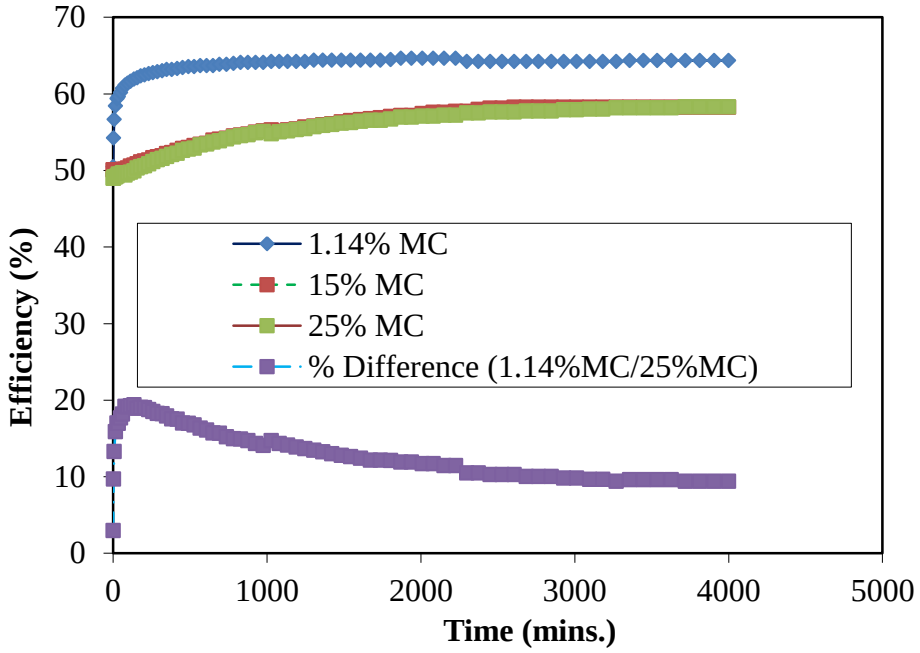

Figure 4.8 Simulated impact of moisture content on conversion efficiency.

Moisture content has a very important influence on conversion efficiency and gasifier design requirements [Mamphweli, 2009]. As the moisture content increases the conversion efficiency decreases considerably as evident from figure 4.8. Maximum conversion efficiency was achieved at low moisture content (1.14%). This observation can be explained by the reaction kinetics. Again, as explained earlier in section 4.8.1, a high quantity of energy is consumed during the drying process of the material and the energy is no longer available for the reduction reactions to take place. However, the reduction in CO as mentioned earlier, implied a reduction in conversion efficiency and the gain in hydrogen could not compensate for the loss in CO content. The volume of the combustible gases in the syngas largely influences the gas heating value. This in turn

influences the conversion efficiency of the gasification process because the gas heating value is directly proportional to the conversion efficiency of the gasifier. At higher moisture contents (15% and 25% respectively), the low oxidation temperature inhibiting the rate of reaction is compensated by a high water (H_2O) concentration which accelerates the water – gas shift reaction (equation 9, chapter 2). The percentage difference between 1.14% moisture content and 25% moisture content is approximately 20% in terms of efficiency. This value is significantly higher when compared to that of 15% and 25% moisture contents.

4.8.3 The impact of particle diameter on conversion efficiency

Particle diameter has an impact on the burning characteristics of the fuel because it affects the rate of heating and drying during gasification [Ciolkosz, 2010]. Figure 4.9 shows the impact of particle diameter on conversion efficiency of the gasification process obtained through computer simulation using the same parameters presented in table 3.2 and 4.4. The particle diameter was varied between 6 cm, 20 cm and 30 cm respectively.

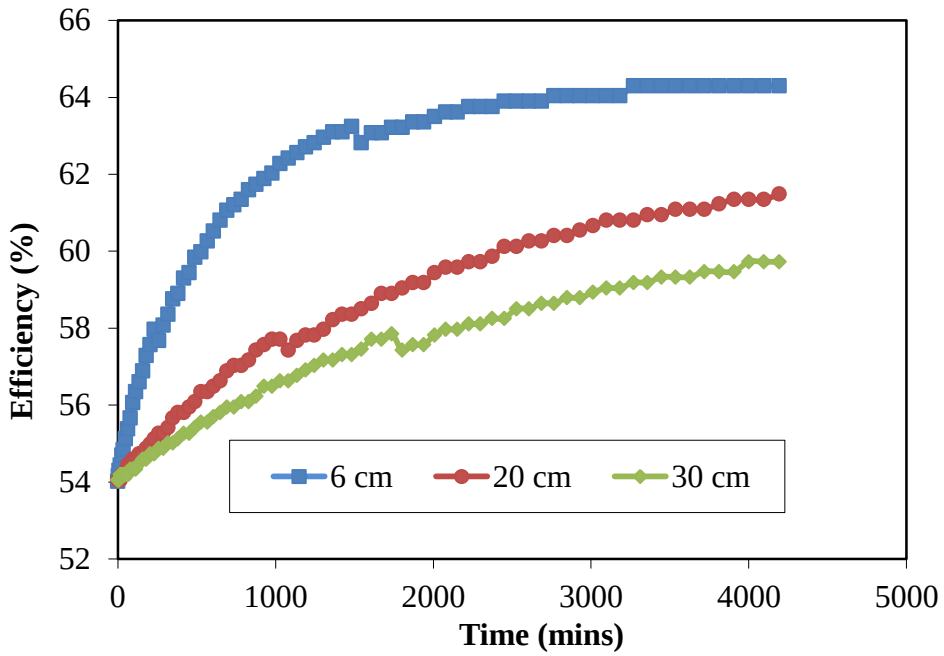

Figure 4.9 The impact of particle diameter on conversion efficiency.

It can be observed from figure 4.9 that conversion efficiency increases with smaller particle diameters (6 cm), compared to larger particle diameters (20 cm and 30 cm respectively). Smaller particle diameters have larger surface area per unit mass and larger pore sizes which facilitates faster rates of heat transfer and gasification [Kirubakaran *et al*., 2009]. For larger particle diameter to achieve maximum conversion efficiency longer reactor length is needed. Smaller particle diameters are more likely to be converted into gases completely because of their size and diffusion limitations during reaction processes [Kumar *et al*., 2008]. Thus gasifiers with shorter reactor lengths need small particle diameter to achieve maximum conversion efficiency.

4.8.4 The impact of temperature of input air on conversion efficiency

According to Arrhenius law of kinetics, increasing temperature increases the rate of reaction. Gasifiers are generally operated at ambient air temperature of 27ºC (300K) [Jayah, 2002]. Figure 4.10 shows the impact of temperature of input air on conversion efficiency. This was simulated using the parameters presented in table 3.2 and 4.4 respectively, with only temperature of input air varied from 27°C, 627°C and 1227°C.

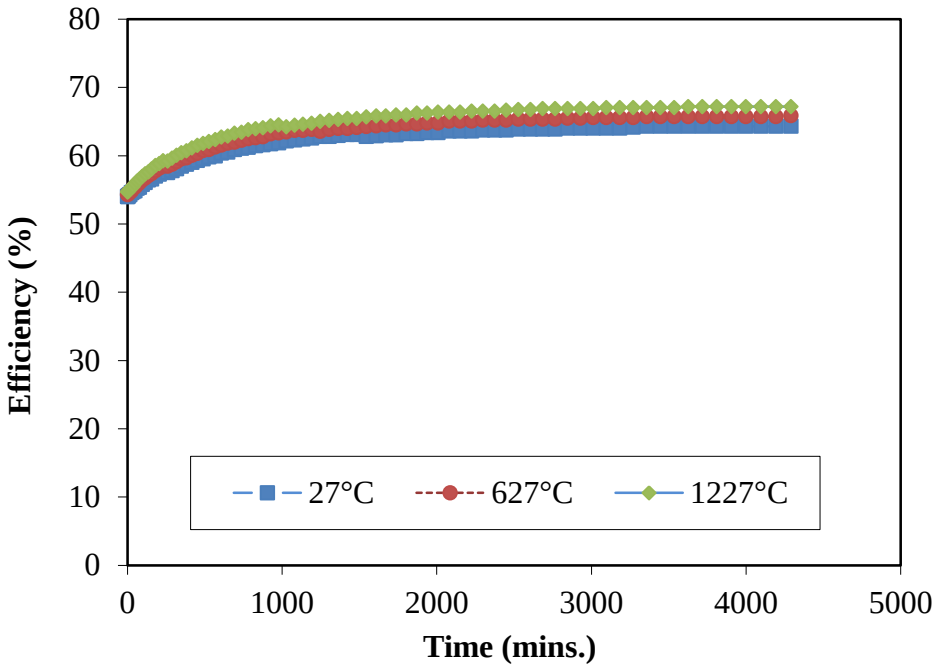

Figure 4.10 The impact of temperature of input air on conversion efficiency.

The gasification reactions explained in chapter 2 (equations 4 - 9) occur simultaneously and the content and ratios of CO, H_2 and CH_4 in the product gas are affected by temperature of the reactants [Kumar *et al.*, 2009]. Conversion efficiency increases as

temperature of input air increases (figure 4.10). This is due to heat, through hot air, brought into the reactants which induce an increase in reaction temperature thereby leading to a reduction in the air – fuel ratio. The conversion efficiency increases from 58% to 60% when the temperature of input air increases from 27°C to 627°C. An experiment was conducted by Mathieu and Dubuisson, 2002 to investigate the impact of temperature of input air on gasifier conversion efficiency. It was found that reaction temperature increased when the temperature of input air increased. The conversion efficiency of gasification increases with increasing temperature of input air [Mamphweli, 2010]. This observation can also be explained by the following trends:

i. The production of CH_4 being exothermic in the hydrogasification reaction (reaction in which carbon reacts with hydrogen to form methane), decreases when reaction temperature and hence temperature of input air increases.
ii. CH_4 consumption with H_2O and CO_2 increases when the reaction temperature and the temperature of input air increases.
iii. CO production in the Boudourd reaction, being endothermic, increases at the expense of C and CO_2 when temperature increases [Mathieu and Dubuisson, 2002].

4.8.5 The impact of throat diameter on conversion efficiency

Figure 4.11 shows the impact of throat diameter on conversion efficiency. This was simulated using parameters presented in table 3.2 and 4.4 respectively, with only the throat diameter varied from 10 cm, 30 cm and 50 cm respectively.

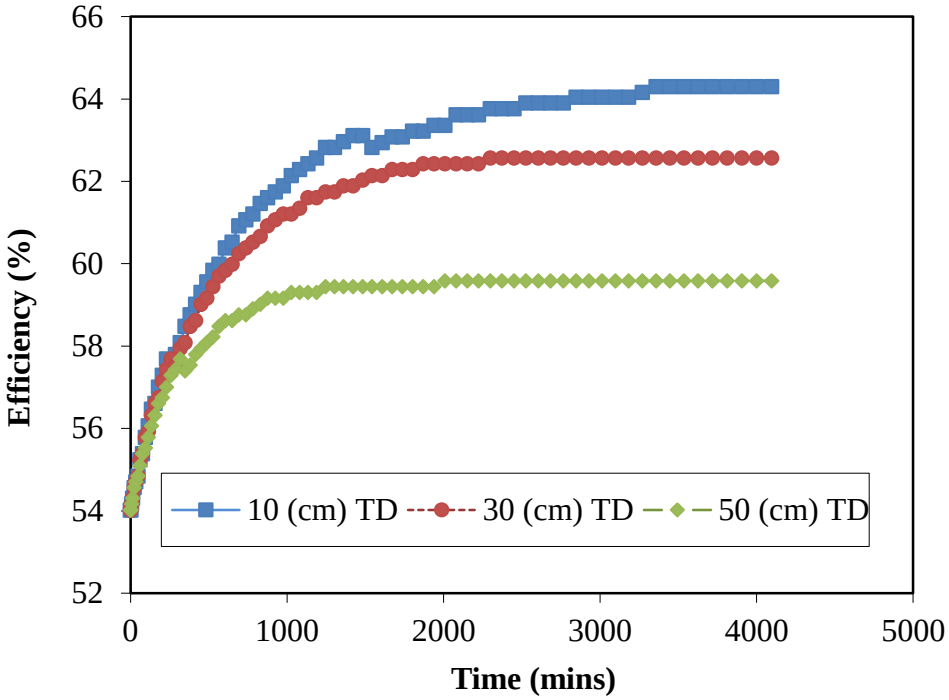

Figure 4.11 The impact of throat diameter on conversion efficiency.

From figure 4.11 it can be observed that the smaller throat diameter (10 cm) results in an increase in conversion efficiency whereas the larger throat diameters (30 cm and 50 cm respectively) results in lower conversion efficiency. This is because lager throat diameters decreases temperature due to divergent effect and hence the rate of reaction. Although smaller throat diameter increases conversion efficiency, it requires longer gasification period to achieve that efficiency [Kumar *et al*., 2008]. The throat diameter is also dependent on the particle size of the feedstock.

4.8.6 The impact of throat angle on conversion efficiency

Throat angle is a special unique feature of the downdraft gasifiers and its impact on conversion efficiency is important [Kumar, 2008]. However, the main purpose of the

throat in a downdraft gasifier is to distribute heat evenly around the combustion zone and consequently along the gasification axis. This heat distribution is important for optimum conversion efficiency [Mamphweli, 2009]. Figure 4.12 shows the impact of throat angle on conversion efficiency at 25, 40 and 90 degrees respectively, also obtained through computer simulation of the gasification process using the parameters presented in table 3.2 and 4.4 respectively. Only the throat angle was varied while other parameters remained constant.

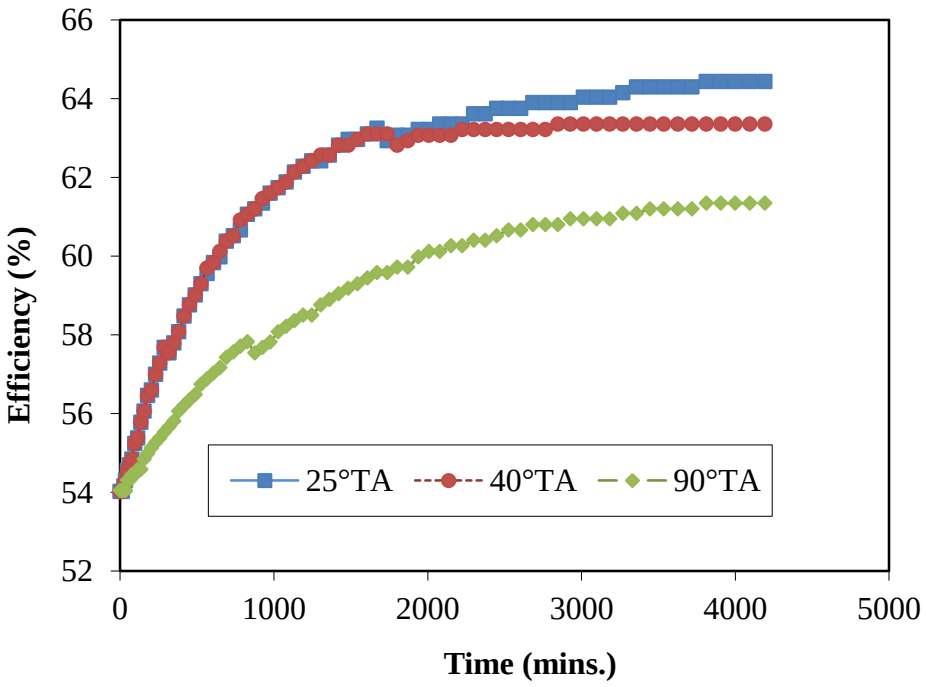

Figure 4.12 The impact of varied throat angle on conversion efficiency.

The smaller throat angle (25º) tend to result in increased conversion efficiency as evident in figure 4.12 whereas the larger throat angles (40° and 90º) decreases conversion efficiency because of their decreasing temperature impact due to divergent effect which

apparently leads to a reduction in the rate of reaction. Although smaller throat angles increase efficiency, it also requires longer gasification period to achieve the maximum conversion efficiency [Kumar *et al*., 2008]. The relationship between throat angle and conversion efficiency of the gasification process was modeled into the gasifier simulation program developed by Jayah *et al* 2003, which was used in this study to conduct computer simulations.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY OF FINDINGS

This research investigated the possibility of gasifying sugarcane bagasse as an efficient conversion technology through determination of the gasification characteristics and properties of sugarcane bagasse. Proximate analysis of the material suggests that moisture content, volatile matter content, fixed carbon as well as ash content, are among the characteristics of sugarcane bagasse. These characteristics are of utmost importance in gasification of sugarcane bagasse and should be within limits suitable for gasification. Elemental composition as described by ultimate analysis is one of the most important properties of biomass because it indicates the theoretical energy content of the biomass. Ultimate analysis of sugarcane bagasse as evident from table 4.2 (carbon, hydrogen, nitrogen and sulfur analyzer) and figure 4.1 (Energy – dispersive x – ray spectroscopy) revealed that the main elemental component of sugarcane bagasse is oxygen which can be attributed to its carbohydrate structure, which is why gasification of sugarcane bagasse occur under much less severe operating conditions because of high reactivity of oxygen. In order to simulate the efficiency of an energy conversion system such as gasification, proximate and ultimate analyses are of importance [Malatji, 2009].

From table 4.1 in chapter 4, volatile matter content increased with increasing heating rate which affected the location of the TGA curve and the maximum devolatilization rate of sugarcane bagasse. The rate of devolatilization depends on heating rate [Galip and

Andrea, 2011]. Again, from table 4.1 in chapter 4, the moisture content of sugarcane bagasse is relatively low which was due to pre drying of the material prior to analysis. High moisture content results in low thermal efficiency [FAO Corporate Document Repository, 1986]. Ash content was also found to be low as can be observed from table 4.1. The low amount of ash makes sugarcane bagasse suitable for gasification [Surinder *et al*., 2003].

The TGA and the DTG indicated that devolatilization of sugarcane bagasse proceeds in three different weight loss stages namely the dehydration, active and passive weight loss stages. The temperature ranges of these stages and the kinetic parameters of the devolatilization depend primarily on the rate of the transfer of heat, the composition of sugarcane bagasse and the degree of the oxidizing environment. It was found that devolatilization mainly occurred in the temperature range 105ºC – 900ºC. Kinetic parameters such as activation energy and pre – exponential factor were evaluated by the model – free kinetic method (Kissinger method). The activation energy and the pre – exponential factor were found to be 181.51 kJ/mol and 3.1×10^3/min. The reason for kinetic analysis stem from the fact that reasonably accurate values of the kinetic parameters are necessary when designing and developing thermochemical conversion systems for biomass. The values of the kinetic parameters were used to predict the progress of the reactions giving product compositions at different zones along the gasifier, taking into account gasifier geometry as well as its hydrodynamics.

The heating value of sugarcane bagasse was measured and found to be 17.8 MJ/kg which was used during calculation of the conversion efficiency of the gasification process. It was found that conversion efficiency depended on energy content of the material under study as well as conditions of the gasifier operating parameters. Conversion efficiency was calculated by dividing the energy carrier output by the exergy of the feedstock input.

Scanning electron microscope also revealed the rigid and compact morphology of sugarcane bagasse as well as the shape, size distribution and roughness of the surface of different parts of the material. The size and shape of sugarcane bagasse have an influence on the transfer of heat into the material and on the rate of phase changes as well as on gas escape from the material. To ensure a good heat transfer and minimal temperature gradient the material should be closely in contact with the heat transfer surface [Stenseng *et al*., 2001].

Computer simulation of the gasification process showed that several characteristics affect the gasification process and performance of sugarcane bagasse including moisture content, particle diameter, chemical composition as well as gasifier operating parameters such, throat diameter, throat angle and temperature of input air. Results showed that these parameters are quite interrelated. Gasification rate, process efficiency and gas heating value are affected by each of these parameters. Gas volume increased at reduced moisture content and the gas heating value is largely influenced by the volume of combustible gases in the syngas which in turn influences the conversion efficiency of the gasification process as evident in figure 4.6. The simulated gasifier conversion efficiency in figure 4.7

also revealed that conversion efficiency is enhanced at low moisture content as conversion efficiency of the gasification process increased with a decrease in moisture content. This observation was explained by the reaction kinetics of the simulated gasification process.

Gasifier operating parameters such as temperature of input air, throat angle, and thraot diameter were also found to have an impact on conversion efficiency of the gasification process. Conversion efficiency increased slightly with increasing input air temperature due to additional enthalpy needed for reaction to occur. Furthermore, maximum conversion efficiency was achieved at reduced throat angle and throat diameter (65% at throat angle of 25º and 65% at thraot diameter of 10 cm respectively).

5.2 SUMMARY OF CONTRIBUTIONS

There is a lot of information about the gasification of other biomass materials and coal than sugarcane bagasse. This is basically because trials with this feedstock faced challenges with the handling of silica, hence a reduced interest in its gasification characteristics and properties. This research has added information on the gasification characteristics and properties as well as the impact of various gasifier design parameters and operating conditions on the gasification efficiency for sugarcane bagasse. The simulation results gave an idea about an efficient sugarcane bagasse gasifier at laboratory scale. A large scale gasifier with enhanced conversion efficiency can be designed using the simulation results.

5.3 CONCLUSION

This research investigated the possibility of gasifying sugarcane bagasse as an efficient conversion technology through the investigation of the properties of sugarcane bagasse and also through computer simulation of the gasification process. The study emphasized the need for understanding the fuel properties and characteristics in order to develop an efficient gasification system. The study also established that the chemical properties of sugarcane bagasse meet the minimum requirements for gasification in a downdraft gasifier suitable for electricity generation although it is expected that the silica could result in ash fouling and/or slagging during the actual gasification. The activation energy as well as the pre – exponential factor both gave good values required to start the reaction leading to the syngas formation and the frequency of particle collision within the gasifier. The optimum gasifier operating conditions for enhanced conversion efficiency were also established. These operating conditions include low moisture content in the material, reduced throat angle and throat diameter as well as reduced particle diameter and increased temperature of input air. It was also established that the processing of sugarcane bagasse needed before gasification include drying and briquetting to the required size to allow for gravity feed in the gasifier.

5.4 RECOMMENDATION FOR FUTURE RESEARCH

This research successfully investigated the gasification characteristics and properties of sugarcane bagasse. It was established that theoretically sugarcane bagasse meets the minimum requirements for gasification in a downdraft gasifier, however the research did not involve the actual gasification of the feedstock, and this is where many challenges

could be experienced. It is therefore recommended that research be undertaken on gasification experiments for sugarcane bagasse.

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APPENDIX A: RESEARCH OUTPUTS ASSOCIATED WITH THE WORK

The research outputs associated with this work is as follows:

A1: JOURNAL PUBLICATIONS

A1.1 Submitted/Accepted papers

I. Anthony Anukam; Edson Meyer; Sampson Mamphweli; Omobola Okoh (2013). Gasification of sugarcane bagasse as an efficient conversion technology for the purpose of electricity generation. *Journal of the University of Fort Hare, Vol 20, No. 1, ISSN: 0015 – 8054.*

II. Anthony Anukam; Sampson Mamphweli; Edson Meyer; Omobola Okoh. Computer simulation of the mass and energy balance during gasification of sugarcane bagasse (*In press: Journal of Energy: Article No. 713054*).

III. Anthony Anukam; Sampson Mamphweli; Polycarp Mabizela; Edson Meyer. The properties and suitability of various biomass and coal blends for electricity generation through co – gasification in a downdraft gasifier system (*Under preparation*).

A2: CONFERENCE PROCEEDINGS

A2.1 South African Institute of Physics Conference (under review)

I. Anthony Anukam, Edson Meyer, Sampson Mamphweli, Omobola Okoh. Gasification characteristics of sugarcane bagasse. 57th SAIP Conference, University of Pretoria, South Africa, (2012).

A3: CONFERENCE PRESENTATIONS

A3.1 National Conference on Global Change

I. Anthony Anukam, Sampson Mamphweli, Edson Meyer, Omobola Okoh. Characterization of sugarcane bagasse for gasification purposes. National Conference on Global Change, Boksburg, Johannesburg South Africa (2012).

A3.2 SACI/ASPEN PHARMACARE/LASEC

I. Anthony Anukam, Sampson Mamphweli, Edson Meyer, Omobola Okoh. The possibility of gasifying sugarcane bagasse as an efficient conversion technology. Annual Post – Graduate Chemistry Seminar, Walter Sisulu University, South Africa (2012).