PERFORMANCE MONITORING OF A 150KVA BIOMASS GASIFIER SYSTEM AT MELANI VILLAGE, EASTERN CAPE, SOUTH AFRICA

University of Fort Hare
Together in Excellence

A dissertation submitted in fulfillment of the requirements for the degree of

MASTERS OF SCIENCE

By

NWABUNWANNE LILIAN NWOKOLO

In the Faculty of Science and Agriculture at the University of Fort Hare

Supervisor: Dr S. Mamphweli

Co-Supervisor: Prof E. Meyer

December: 2013

DECLARATION

I, Nwabunwane Lilian Nwokolo, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or in part submitted it at any other university for a degree.

Signature -- Date 22|4|2014 --

DEDICATION

To God be the glory for the completion of this study

ACKNOWLEDGEMENT

First and foremost I offer my sincerest gratitude to my supervisor, Dr Sampson Mamphweli, who has supported me throughout this project with his patience, knowledge and guidance. I attribute the level of my Masters degree to his encouragement and effort and without him this dissertation, too, would not have been completed or written. One simply could not wish for a better or friendlier supervisor. My sincere thanks also go to my co supervisor, Prof Edson Meyer for his understanding and accommodation.

I also acknowledge the University of Fort Hare and Eskom for the implementation of the Johansson biomass gasifier where my projec[illegible] In addition I thank all the staff and student at Fort Hare institute of Technology for their assistance.

My sincere thanks also go to my family for their love, care and prayers. I'm grateful to God am a part of them. I would like to express my gratitude and respect to Dr Nnamdi Chigor whose advice and insight was of great value. Finally I would like to say thank you to all my friends.

SUMMARY

The economic development of any community or society at large is directly linked to energy availability and usage. Concern for climate change due to intense use of fossil fuel for energy production has increased interest in alternative energy technologies such as biomass gasification. The system Johansson biomass gasifier at Melani village in Eastern Cape South Africa was piloted to establish the techno-economic viability of biomass gasification for electricity generation in South Africa. Besides this it was also implemented to improve the socio-economic conditions of the community by providing them with low cost electricity that can drive small businesses such as a Bakery.

This system utilizes chunks of wood coming from a saw mill industry located nearby, which produces large quantities of biomass waste that pose a challenge in terms of disposal. From time of implementation till now there is no performance information about this particular technology therefore this present study evaluated the performance of the system when operated on a full electrical load and when powering the bakery. A custom-built gas and temperature profiling system was used to measure the gas profiles from which the gas heating value was calculated. A bathroom scale was used to measure the quantity of wood fed into the gasifier. A dummy load bank was constructed using twelve 12 kW water heating elements connected such that they draw maximum power from each of the three phases. A power meter was used to measure the current, voltage, power as well as energy from the generator during operation.

The system was found to be producing power above its power rating of 120 kW when it was operating at full load. It was also found that on average 1.075kg of wood resulted in 1 kWh of electrical energy. The system achieved a cold gas efficiency of 88.11% and an overall efficiency of 20.1% due to the efficiency of the engine.

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LIST OF ABBREVIATIONS

GHG – Greenhouse Gas

BFB – Bubbling Fluidized Bed

CFB – Circulating Fluidized Bed

CO_2 – Carbon dioxide

CO – Carbon monoxide

H_2 – Hydrogen

CH_4 –Methane

N_2 – Nitrogen

O_2 - Oxygen

GTPS – Gas and Temperature Profiling System

Pd/Ni – Palladium/Nickel

NDIR –Non-Dispersive Infrared

CV –Calorific Value

AC – Ash Content

VM – Volatile Matter

OM – Organic Matter

ER – Equivalence Ratio

HHV – Higher Heating Value

TGA – Thermogravimetric Analysis

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Presently the world relies heavily on fossil fuels such as coal, petroleum and natural gas for its energy needs. In South Africa, electricity generation lies solely in the burning of coal, which adds to the global carbon dioxide (CO_2) emission. In 2008 out of a 50.2 GW of power generated by Eskom, coal accounted for 42.5 GW. South Africa meets most of its energy needs through burning of coal probably because of its large deposit when compared to conventional oil and natural gas [Energy Information Administration, [illegible]]. The side effect is the carbon footprints this leaves behind which contributes immensely to Global warming. South Africa is at the 13th position out of 50 countries regarding its contribution to global warming through greenhouse gas (GHG) emission [Ziuku, 2011].

Besides burning of coal for electricity generation, direct burning of coal for heating and cooking which is mostly common to low income houses in South Africa also contributes to CO_2 emission [Energy and development group, 2013]. The present environmental challenges such as change in rainfall pattern, abnormal sea rising and increase in temperature facing the world at large are all product of GHG emissions. This planetary changes if not put to a check can be highly disastrous in the near future [Energy and development group, 2013]. South African department of energy in its bid to address this issue have developed a white paper on renewable energy and clean energy which is geared towards diversification for a less carbon intensive energy production [Department of Environmental Affairs and Tourism, 2004].

The use of biomass for energy generation has the potential to reduce green house gas emission which is a significant contributor to global warming. This is because the carbon dioxide released during the combustion of biomass is recaptured during the growth of new biomass thereby rendering the process carbon neutral [Yokoyama *et al*, 2000]. Although the use of biomass can't fully replace fossil fuels which we use at present, it can produce fuels and chemicals that are comparable to that produced from fossil fuels. Biomass is a natural substance that stores solar energy through a process known as photosynthesis. They include all biological material from living or dead plants.

Biomass energy is majorly sourced from wood and wood waste, which includes forest and agro-industrial plantations, bush trees and farm trees, but other sources still exist. These include crop residues such as straw, leaves and plant stem, processing residues such as sugarcane bagasse, saw dust, husk and nutshell, and municipal solid waste [Gokcol *et al*, 2009]. Wood accounts for about 64% of the energy produced from biomass, followed by solid municipal waste with about 24%, and lastly land filled gases and agricultural waste accounting about 5% respectively. Africa as a continent has an abundant supply of different types of biomass suitable for energy production [Amigun *et al*, 2010].

Biomass is one of the most promising renewable energy sources due to the advantages it possesses and offers, it reduces our dependency on oil which is a non-renewable resource, it cuts down the amount of waste sent to landfill, emits lesser carbon dioxide as compared to fossil fuel. Biomass derived energy can meet a wide range of energy need such as electricity generation, production of liquid fuel for transportation, and production of chemical and process heat for industrial purposes when properly utilized.

Since ancient time, biomass has been utilized for heating and cooking through direct combustion. This practice is still ongoing mostly in rural communities of the developing countries. Today a number of conversion technologies are available; these technologies may release energy in the form of heat or electricity, or in the form of combustible gas or liquid biofuel through biological or thermochemical means. Biological conversion uses mostly moist raw material with high cellulose content while thermochemical conversion method uses a wide range of biomass materials [Dasappa, 2011]. Some of these technologies are gasification, combustion, co-firing, pyrolysis, fermentation or hydrolysis, etherification or pressing and anaerobic digestion [Gokcol *et al*, 2009]. This study is focused on gasification only.

Biomass gasification is a partial combustion of biomass (carbon containing materials) to produce a gaseous product known as producer gas or syngas which can be used for production of electricity, liquid fuel and fine chemicals. This is a thermochemical conversion process since the biomass materials are heated at high temperature. The gas resulting from this process contains carbon monoxide, hydrogen, nitrogen and traces of methane. Gasification is made possible in a high temperature gasifier or reactor which comes in different design. These designs are based on the direction of gas flow and the way the oxidizing agent is introduced into the gasifier [Sharma, 2009]. The gas mixture differs also due to the gasification agents used. Figure 1.1 shows the classifications of gasifiers

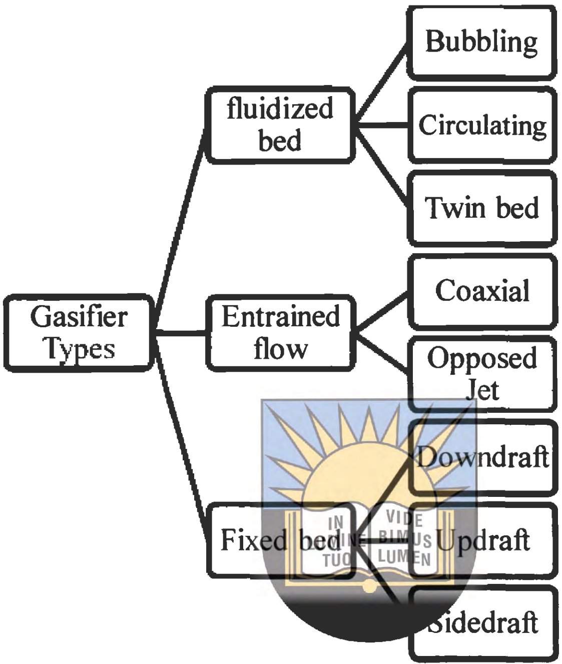

Figure 1.1: Classifications of Gasifier Systems

Fluidized bed is further divided into bubbling fluidized bed (BFB), circulating fluidized bed (CFB), and twin bed. Entrained flow is further divided into coaxial down flow and opposed jet. Fixed bed is divided into downdraft, updraft and cross or side draft. Each of these gasifiers has their inherent advantages and disadvantages, for instance fluidized bed is more tolerant with particle size but operates at low temperature during gasification that leads to high tar formation and incomplete conversion of char. The opposite is the case for entrained bed as it is less tolerant of particle size but operates at high temperature. Fixed bed is tolerant of particle size but is faced with the problem of high tar formation with the exception of downdraft gasifier [Heiskanen, 2011].

Downdraft gasifier offers the advantage of low tar concentration in the producer gas. This is due to the gas having to pass through the high temperature combustion zone where the tars are cracked and converted into useful gases. In addition it offers high char conversion and low ash carry over. However this type of gasifier is limited to small scale because of the difficulties associated with uniform distribution of air in reactors with large diameters [Martinez *et al*, 2012]. This project aims at monitoring the technical performance of a 150 kVA biomass downdraft gasifier system.

1.2 GASIFICATION PROJECT

The economic development of any community or society at large is directly linked to energy availability and usage. South Africa's rural areas are endowed with biomass waste which mostly emanates from saw mill industries located in such areas [Mamphweli and Meyer, 2009]. These wastes are burnt in furnaces as a means of waste management however this practice result in some environmental problems such as greenhouse gas emission, accumulation of tars and soot in the windows of some nearby houses. To eliminate these challenges and to meet the socio-economic need (low cost electricity for small businesses) of the people living at Melani village, Eskom and University of Forte Hare initiated a biomass gasification pilot plant project. This project was aimed at installing a 150 kVA biomass downdraft gasifier system alongside a community bakery. The project has been completed and it is fully operational. This study is aimed at evaluating the performance of the biomass gasifier system.

1.3 PROBLEM STATEMENT

The performance of a thermochemical conversion technology is measured through its conversion efficiency. The same applies to gasification in a downdraft gasifier for which this research is focused. This parameter depends on reactor design, fuel properties as well as gasifier operating conditions. Amongst the operating conditions, equivalence ratio known as the fuel to air ratio influences the temperature of the reactor and quality of syngas generated during gasification. For instance using air as an oxidizing agent increases the concentration of nitrogen and reduces the calorific value of the producer gas while using oxygen or steam increases the concentration of combustible components in the producer gas and calorific value. Besides oxidizing agent, chemical reaction kinetics also play a role in determining the concentration of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4) in the producer gas. These combustible gases are necessary for the syngas to be suitable for engine operation. Furthermore gasifier design features, such as throat diameter have a relation with particle size, which in turn determines chemical reaction rate. To efficiently convert solid fuel into high quality producer gas required for electricity generation as is the case of Johansson biomass gasifier system, gasifiers operating conditions and design plays an important role. Therefore it is important to evaluate the performance of these systems.

1.4 RESEARCH OBJECTIVES

This study was aimed at evaluating the performance of a 150 kVA biomass gasifier system installed at Melani village. To do this the following aspects were studied:

(i) The proximate and ultimate analysis of the eucalyptus wood used for the study.

(ii) Analysis of the gas resulting from the gasifier before entering the engine.

(iii)Mass and energy balance of the system was evaluated when the gasifier was operated on full load.

(iv)The cold gas efficiency as well as the gas to engine (electrical) efficiency of the system.

(v) The emission characteristics of the engine used.

1.5 RESEARCH QUESTIONS

(i) What are the physical and chemical properties of the eucalyptus wood used for the study?

(ii) What are the syngas composition and its heating value?

(iii) What is the mass and energy balance of the gasifier?

(iv) What thermal and electrical efficiency is achieved by the gasifier when fed with eucalyptus wood?

(v) What are the gases coming out of the engine and how do they compare to those going inside the engine.

1.6 RESEARCH METHODOLOGY

1.6.1 Gas analysis, ultimate and proximate analysis

The mass of the feedstock was determined using bathroom scale before feeding into the gasifier hopper. The ultimate and proximate analysis was undertaken to determine the physical and chemical properties of the eucalyptus wood used for this study. The calorific value of the material was determined using a CAL2K oxygen bomb calorimeter.

Gas analysis was undertaken using a custom-built Gas and Temperature Profiling System (GTPS), which employs non-dispersive infrared gas sensors for measurement of methane, carbon monoxide and carbon dioxide. The GTPS employs a Palladium/Nickel (Pd/Ni) gas sensor for measurement of hydrogen. The differential voltage outputs are logged into a CR1000 data logger interfaced to a computer. The data is then downloaded into the computer and calibrated to percentage composition [Mamphweli and Meyer, 2013]. The gas calorific value was determined from the percentage composition of combustible gases.

The electrical performance of the generator was measured using a portable energy meter which is capable of providing the load profiles of the three generator phases. The energy meter recorded all the energy parameters from the three phase generator at a preset interval of one minute. The recorded data usually present in diverse formats was downloaded into the computer via the powerTrack software for analysis.

1.7 SIGNIFICANCE/RATIONALE

There are a number of biomass gasifiers operating around the world. The system Johansson biomass gasifier was piloted to establish the techno-economic viability of biomass gasification for electricity generation in South Africa. There was no performance information about this particular technology until this research was undertaken. The information available was limited to the gas analysis as well as thermal efficiency studies on a 60 kW system that was not operated at full load. This research has therefore provided information on the technical performance of the gasifier.

1.8 DELINEATION AND LIMITATION

The study evaluated the performance of the 150 kVA biomass gasifier. It involved the proximate and ultimate analysis of the feedstock used, the mass and energy balance as well as efficiency investigation. The study was under taken with the engine/generator running at full load using electrical heating elements to draw maximum power from the generator, however in real operational conditions; the generator operates at the maximum of 80% capacity. The full load operation was undertaken to establish the system performance under extreme conditions.

1.9 ASSUMPTIONS

It was assumed that the biomass gasifier would achieve thermal efficiency above 70% and electrical efficiency above 20% when operating at full load. These assumptions were made based on the design manual claims and studies undertaken on a similar design but smaller size gasifier of 60 kWe.

1.10 DEFINITION OF TERM

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

Biomass Gasification is the partial combustion of biomass material under a controlled supply of oxidants defined herein (air, oxygen and steam) to produce gaseous fuel usually referred to as syngas or producer gas. It is a renewable means of meeting energy need [Martinez *et al* 2012].

Cold gas efficiency is the percentage of the energy content of wood that is converted to producer gas. It is an important parameter in gasification as it is dependent on a number of factors [Raman *et al*, 2013].

Gasifier system refers to the gasifier process components including the reactor and all downstream processing components [Sharma, 2008].

Equivalence ratio is the ratio of actual volume of air used for wood gasification to the volume required for complete combustions of the wood [Raman *et al*, 2013].

Mass Balance is the ratio of total mass of output material to the total weight of input material. It quantifies the mass flow of material through a gasifier [Dogru *et al*, 2002].

1.11 DISSERTATION OUTLINE

This section summarizes the chapters of this dissertation and provides an overview of the scope of the study.

Chapter one presented the objective of the research which is to evaluate the performance of Johansson biomass gasifier system situated at melani village Eastern Cape, South Africa. The method employed in achieving the aim of the study was briefly introduced. Lastly the significance of the study as well as some terms used was clearly defined.

Chapter two presents a synthesis of literature on the properties of biomass materials. The various types of biomass gasifiers have also been discussed and this included Fluidized bed, entrained flow and fixed bed gasifiers. The fixed bed downdraft gasifier was further discussed in detail since this research focuses on this type of gasifier. Some of the output parameters that influence gasification efficiency, producer gas composition, gas yield and calorific value of the gas produced in a fixed bed gasifier were also discussed.

Chapter three presents the various methods employed in data collection, these include the ultimate and proximate analyses. Explanation of how the gasification of eucalyptus wood occurs in the Johansson downdraft gasifier has been provided in this chapter. The measuring technique employed by the Gas and Temperature Profiling System (GTPS) used for the gas analysis has been provided. The mathematical relations used in determination of mass and energy balance of the system as well as the different stages of efficiencies are all stated in this chapter.

Chapter four presents the results obtained for this study; these include the ultimate and proximate analysis results. Analysis of the gas produced during the operation of the biomass gasifier system is also presented in this chapter. The mass and energy balance analysis are presented. The cold gas efficiency, electrical efficiency and co-generative efficiency are also presented. The emission characteristics of the engine are also discussed in this chapter.

Chapter Five presents the summary, conclusions and recommendations of the study. This is where the major findings of the research are presented, and a conclusion drawn from these findings is also presented. The conclusion was based on the objectives of the study and the research questions.

CHAPTER TWO

LITERATURE REVIEW

2.1 BIOMASS COMPOSITION

Biomass is an organic material that stores solar energy through photosynthesis and in turn creates a source of energy in the form of carbon, hydrogen and oxygen compound. It contains less carbon but more oxygen and a lower heating value than the conventional fossil fuel [Chopra and Jain, 2007]. Biomass comprises of cellulose, hemicelluloses, lignin and other extractives in varying quantities and differs from one plant species to another. These compositions also have different chemical structures which are responsible for difference in their thermal behavior. Figure 2.1 shows the structure of cellulose

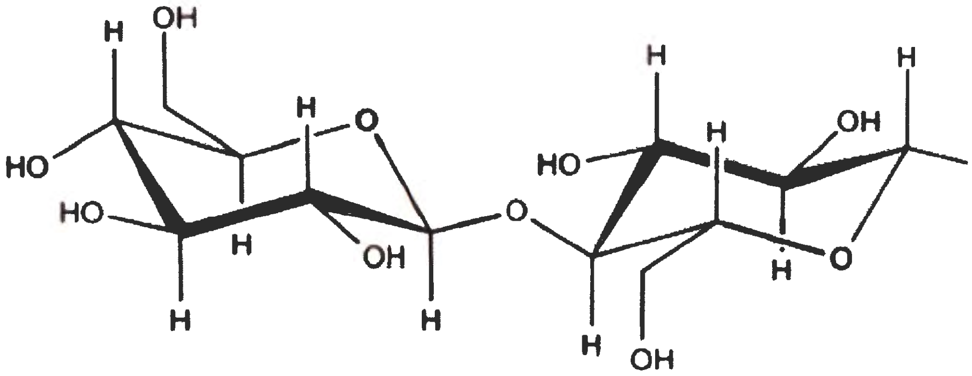

Figure 2.1: Chemical structure of Cellulose [Lin et al, 2013]

Cellulose, the highest in proportion comprises about 40% - 60% of biomass by weight [Yang *et al*, 2007]. It consists of a long chain of glucose that are polymerized together such as D-glucose sugar linked by β-1, 4 glycosidic bonds and a molecular weight of around 100,000. It has an elemental formular that is close to that of hemicellulose and is given as $C_6H_{10}O_5$. During thermal degradation cellulose experiences a rapid decrease in mass within a narrow temperature range of 473K – 673K. This is attributed to the branched chains of polysaccharide that cellulose comprises of which are easily volatilized. Additionally cellulose results in a higher yield of carbon monoxide whereas lignin results in higher yield of hydrogen and methane. This therefore indicates the impact of these compositions [Lv *et al*, 2010]. In a study by Wu et al cellulose pyrolysis/gasification resulted in a higher yield of gas when compared to hemicelluose and lignin. Figure 2.2 shows the chemical structure of hemicellulose

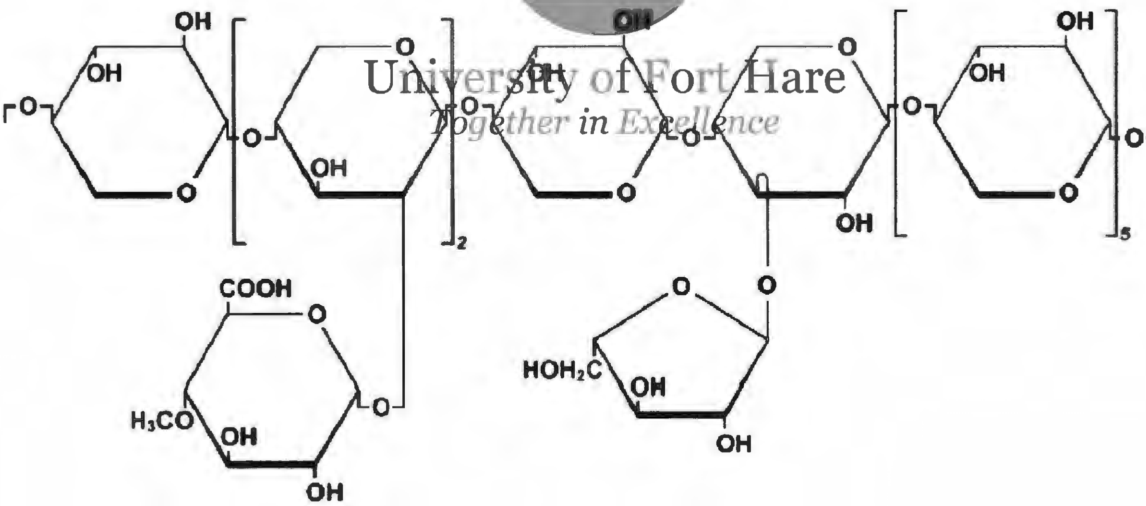

Figure 2.2: Structural representation of Hemicellulose [Jansen, 2011]

Hemicellulose is a branched polysaccharide consisting of glucose and other sugars such as mannose, xylose, arabinose, methylglucuronic and galaturonic acids. It is usually referred to as cross linking glucans because it forms a hydrogen bond with cellulose and lignin. Its molecular weight is less than 30,000 and accounts for 25% - 35% of the biomass material by weight for softwood [Pasangulapati *et al*, 2012]. Hemicellulose degradation temperature and thermal degradation rate is lower when compared to cellulose. Its degradation begins at a temperature of about 180°C and beyond this temperature it decomposes into gases and acetic acid [Garcia-Maraver *et al*, 2013].

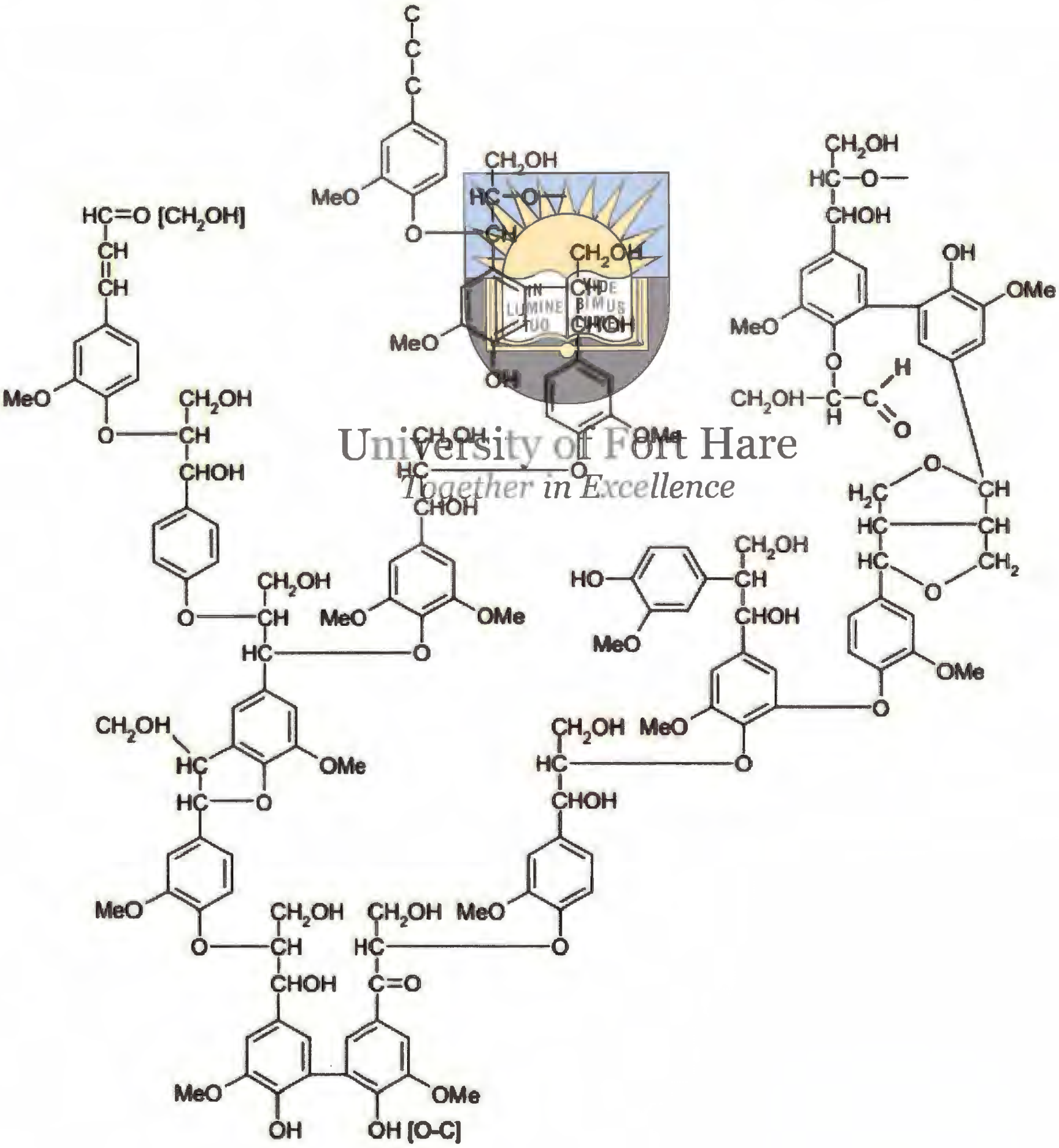

Figure 2.3: Lignin Chemical structure [Alder, 1977]

Lignin which occurs throughout the plant cell wall consists of polymers which are mostly formed by phenylpropane units. It is also a binding material that provides elasticity and strength to biomass material such as wood [Pasangulapati *et al*, 2012]. The proportion of lignin and cellulose determines the suitability of a biomass material as an energy crop [McKendry, 2002a]. Furthermore, lignin has been found to be the main controlling factor during thermal degradation as it controls the decomposition rate of biomass, its product yields and composition.

Lignin unlike cellulose and hemicellulose degrades constantly at a wide temperature range and does not degrade completely up until a temperature of about 973 K [Burhenne *et al*, 2013]. Raveendran *et al* [1996] further confirmed that the thermal stability of lignin is higher than that of cellulose and hemicellulose. This is attributed to the cross linking between the phenylpropane units in lignin [Pasangulapati *et al*, 2012]. Thermal decomposition of biomass materials with high content of lignin are dominated by endothermic reactions while those with low content of lignin such as herbaceous biomass involves more of exothermic reactions [Burhenne *et al*, 2013].

Biomass is a renewable and sustainable energy source that is characterized by low sulfur content, low ash content, high volatile content and high alkali content such as sodium and potassium. Conversion of biomass into fuel gas (biogas and producer gas) can be done via multiple routes, which are mainly categorized as thermochemical conversion and biochemical conversion processes [McKendry, 2002b].

Biochemical conversion involves the fermentation of plant material with the use of yeast or genetically modified microorganism to produce ethanol and anaerobic digestion of plant material to produce methane, but this is outside the scope of this study. This study is geared towards thermochemical conversion which involves some chemical reaction induced by temperature and pressure but focuses on biomass gasification as an efficient thermochemical process for power generation.

2.2 GASIFICATION OVERVIEW

Biomass gasification is a thermochemical conversion process in which solid carbon based feedstocks are converted to a mixture of combustible gases, which primarily consist of carbon monoxide and hydrogen, with lesser concentrations of methane, carbon dioxide, water, nitrogen and hydrocarbons, with nitrogen as the dominating [illegible] when air is used as the oxidizing agent. This type of thermochemical conversion process involves the reaction of biomass material with a controlled supply of air, oxygen, steam or a mixture of them at relatively high temperature and pressure [Martinez *et al*, 2012]. Biomass gasification can be economically valuable where the biomass resources are freely available or available at a low-cost. In most cases this material is available as waste. It is appropriate for decentralized energy system.

Gasification of biomass is an attractive technology because of the diverse application of the fuel gas it produces. These gases can be burned directly for production of heat, utilized as fuel in a gas engine or gas turbine for electricity generation and lastly for production of chemicals [Guo, 2004]. It offers more advantage over direct burning of biomass. The use of biomass for energy production is an old technology, but recently has drawn increasing attention due to its renewable nature, carbon dioxide neutrality, availability and need for energy independence. Gasification of biomass undergoes four major stages regardless of the type of the gasifier system in which the process is taking place. Figure 2.4 shows the various stages of the gasification process.

Figure 2.4: Flow chart of a gasification process

2.2.1 Drying

Drying of biomass is one of the stages that biomass (feedstock) goes through which gets the feedstock ready for easy combustion. In the drying zone the moisture content of the biomass is driven off by evaporation using the heat generated at the combustion zone. Low moisture content improves the thermal efficiency of a gasifier since minimal heat will be required in evaporation of this moisture. Hence more heat is available for the reduction reactions at the reduction zone [Mckendry 2002 and Jayah et al, 2003].

Usually the maximum allowable moisture content is dependent on the gasification technology used. For instance in downdraft gasifier the maximum allowable moisture is 25% on wet basis while updraft allows a moisture content not more 50% [Pereira *et al*, 2012]. According to Dogru *et al* [2002] drying of biomass within the gasifier is dependent on a number of factors namely: surface area of the fuel, the temperature difference between the feed and the hot gases, the re-circulation velocity, relative humidity of these gases and the internal diffusivity of moisture within the fuel.

2.2.2 Pyrolysis

Pyrolysis degrades the cellulose, hemicelluloses and lignin contents of biomass at different temperature ranges due to difference in their reactivity. At a temperature range of 240-350°C cellulose is degraded to produce anhydrocellulose and levoglucosan products, which further decompose into volatile matter, char and tars. Lignin on the other hand decomposes to produce a higher amount of char than cellulose within a temperature range of 280-500°C. Hemicellulose through thermal decomposition at a temperature of 200-260°C yields a higher amount of volatiles and lesser amount of tars and chars than cellulose [Robbins *et al*, 2012]. The pyrolysis during gasification produces both condensable and non condensable gases which comprises mainly of H_2O, CO_2, H_2 and hydrocarbons [Ruiz *et al*, 2013].

2.2.3 Combustion

Combustion is the process through which the carbon content of a biomass material is oxidized to CO_2 and hydrogen content to H_2O. This is made possible at a high temperature of about 800-1000°C [Robbins *et al*, 2012]. During combustion the chemical energy stored in a biomass material is released as heat which can either be converted into mechanical power for electricity generation or used for space heating. Although combustion is applicable to a wide range of feedstock material, their inherent properties influences this process to a great extent. For instance feedstock materials with moisture content above 50% are termed incombustible [McKendry, 2002b]. These feedstock properties are classified as physical, chemical and thermal properties. Some of the physical properties depend on the species of the biomass and they include feedstock density, porosity, and internal surface area. The remaining physical properties which are related to the manner in which the feedstocks are prepared include particle size, bulk density and shape distribution. Chemical properties include the elemental content of the feedstock material, heating values relating to pyrolysis products and higher heating value (HHV). Lastly thermal properties include specific heat, thermal conductivity and emissivity [Demirbas, 2003].

Combustion involves a series of reactions that occur in the combustion zone often referred as oxidation zone. The exothermic nature of these reactions causes a rapid rise in temperature which in turn makes this region a high temperature zone. This explains the low formation of tar in a downdraft gasifier since the gases pass through this high temperature zone before exiting the gasifier [Dorgu *et al*, 2001]. The resulting products from this zone and the chemical reaction will be shown in the subsequent section.

2.2.4 Reduction

Similar to pyrolysis process reduction reactions occur in the absence of oxygen but at a different temperature range of about 800-1000°C within the reduction zone [Puig-Arnavat *et al*, 2010]. In this zone the partially oxidized product of the combustion zone is allowed to pass through a hot bed of charcoal resulting in some endothermic reaction. These endothermic reactions lower the temperature of the gas produced and in turn lowers the calorific value of the gas [Rajivanshi, 1986]. The reduction reactions when compared to combustion reaction are quite slower.

2.2.5 Gasification reactions

Table 2.1 presents series of chemical reactions that occur during the conversion of biomass into useful products in a gasification system [Ruiz *et al*, 2013].

Table 2.1: Gasification reactions

Reaction type	Heat of reaction	No
Oxidation reactions		
$C + O_2 \rightarrow CO_2$	-394 kJ/mol	R1
$C + ½O_2 \rightarrow CO$	-284 kJ/mol	R2
$H_2 + ½O_2 \rightarrow H_2O$	-242 kJ/mol	R3
$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$	-803 kJ/mol	R4
Reduction reaction		
$C + CO_2 \leftrightarrow 2CO$	+172 kJ/mol	R5
$C + H_2O \leftrightarrow CO + H_2$	+131 kJ/mol	R6
$C + 2H_2 \leftrightarrow CH_4$	+74.8 kJ/mol	R7
$C + ½O_2 \rightarrow CO$	-111 kJ/mol	R8
Shift reaction		
$CO + H_2O \leftrightarrow CO_2 + H_2$	+41.2 kJ/mol	R9
Methanization reaction		
$2CO + 2H_2 \rightarrow CH_4 + CO_2$	-247 kJ/mol	R10
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	+206 kJ/mol	R11
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	-165 kJ/mol	R12
Steam reactions		
$CH_4 + H_2O \leftrightarrow CO + 2H_2$	+206 kJ/mol	R13
$CH_4 + ½O_2 \rightarrow CO + 2H_2$	+36 kJ/mol	R14

These reactions result in a mixture of gases comprising of H_2, CO, CO_2, CH_4, C_2H_4 and some impurities such as nitrogen, sulfur, alkali compound and tars. These impurities depend on the oxidizing agent, type of feedstock, type of gasifier used and operating conditions [Damartzis and Zabaniotou, 2011]. Oxidation reactions are highly exothermic, thus releases the energy required for reduction reactions which are endothermic.

Reaction (R5) and reaction (R6) referred as boudouard reaction and water gas reaction respectively are very important reactions during gasification. Both reactions are favoured by high temperature and low pressure contrarily to reaction R7 that is favoured by low temperature and high pressure. Shift reaction is a bi-directional reaction whose direction depends on the condition inside the gasifier. For instance at high temperature, CO concentration increases at the expense of H_2. Steam reactions are endothermic and proceeds at a slower rate, therefore it requires high quantity of energy and catalyst [Heiskanen, 2011].

2.3 GASIFICATION TECHNOLOGY

In order to gasify the diverse types of biomass materials available different gasification reactors have been developed. Numerous researches on gasification reactors have also led to the development of several designs. Gasifiers are primarily classified into three: entrained flow, fluidized bed and fixed bed, with variations within each type. However they can also be classified based on the following:

- Type of oxidizing agents it utilizes: air blown gasifier, steam gasifier and oxygen gasifier.

- Operating pressure: pressurized and atmospheric.
- Source of heat supply: it can be direct through partial combustion or indirect through a heat exchanger or other external source. [Puig-Arnavat *et al*, 2013].

Regardless of these classifications all gasifiers go through the four gasification processes discussed earlier. The choice of any is determined by the type of fuel to be gasified and the end use of the gas produced.

2.3.1 Entrained flow gasifier

Entrained flow gasifiers are less tolerant of particle size as a result they are commonly used for coal gasification. Figure 2.5 shows diagram of an entrained flow gasifier.

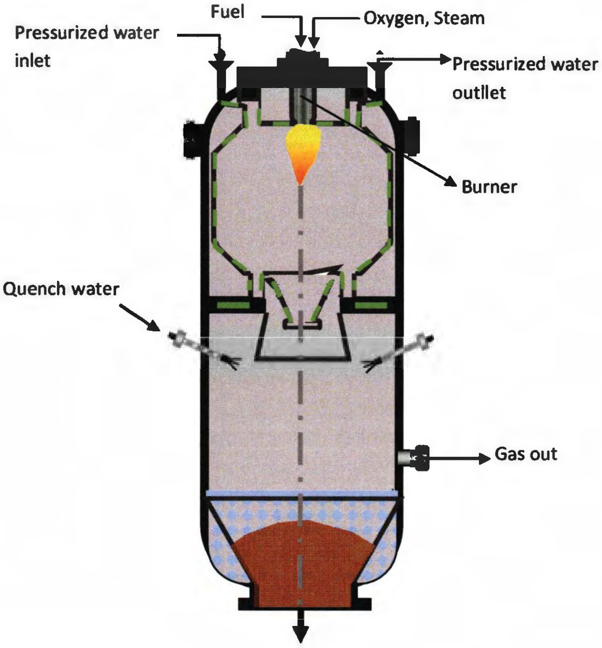

Figure 2.5: Entrained Flow gasifier [NETL, 2006]

They operate at high temperature of about 1200-1600°C and pressure of about 2-8 MPa. This high operating temperature can lead to melting of ash which results in formation of a corrosive substance known as slag. This is why entrained flow is not suitable for gasification of feedstock of high ash content. However its high operating temperature offers the advantage of tar reduction which causes equipment blocking and fouling [Damartzis and Zabaniotou, 2011].

Tar is an undesirable product due to its tendency of condensation at low temperature. Entrained flow gasifiers possess some other characteristics which include short residence time, large capacities which results in high throughput and high oxygen demand. This high oxygen demand is what accounts for the high operating temperature due to the exothermic reaction that exists between the oxygen and the char [Ruiz *et al*, 2013]. In an entrained flow gasifier, oxidizing agents are fed in alongside with finely grinded particles.

2.3.2 Fluidized bed

This class of gasifiers operates at a lower temperature (800-1000°C) than entrained flow, making it suitable for gasification of feedstock of high ash content. Particle size is not a limitation for fluidized bed; it can gasify different types of feedstock hence it is also suitable for large-scale application [Ruiz *et al*, 2013]. Here feed stocks are fed into the gasifier from the top while the oxidizing agents are fed through the bottom in the form of a fluidizing gas. They are both mixed intensely in a hot bed of solid material usually sand. Sand is mostly used because of its high heat retention capability. Their intense and continuous mixture helps to maintain a uniform temperature and heat transfer within the gasifier but does not give room for full conversion of char [Ruiz *et al*, 2013]. Figure 2.6 shows a diagram of fluidized bed gasifier

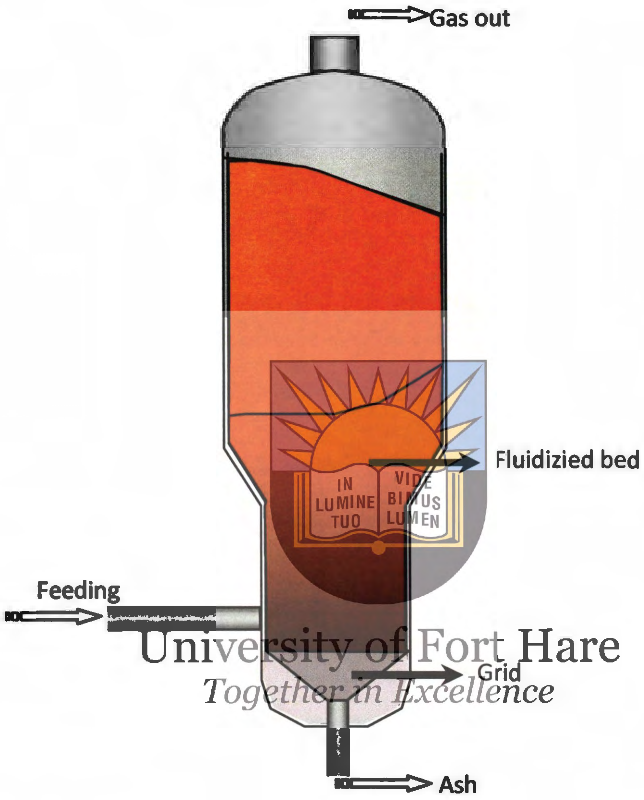

Figure 2.6: Fluidized bed gasifier

Fluidized beds are further classified into circulating fluidized bed (CFB) and bubbling fluidized bed (BFB) based on the fluidization pattern. However a third type known as twin fluidized bed (TFB) is also in existence [Damartzis and Zabaniotou, 2011]. Circulating fluidized bed has a higher throughput which may be attributed to the fact that they operate at a high fluidization velocity. The high fluidization velocity ensures good mixing of gas and solids which in turn promotes an excellent heat and mass transfer [Ju *et al*, 2010].

The bubbling section created in a BFB as the fluidization gas passes through the bed is the center for gasification reactions in this type of gasifier. This bubbles when controlled can improve the heat transfer rate between the gas and the solid [Damartzis and Zabaniotou, 2011]. A twin fluidized bed as the name goes utilizes two reactor beds and as such yields a syngas with higher calorific value when compared to a single bed reactor. This makes it suitable for large scale application. The first bed provides the heat needed for gasifying the biomass in the second bed [Ran and Li, 2012].

2.3.3 Fixed bed gasifier

This conventional type of gasifier consists of a bed of solid fuel that moves down slowly during the gasification process. In fixed bed gasifier, feedstocks are fed into the gasifier system through the top and the oxidizing agent either goes in the same direction or opposite direction with the material. They are characterized by long residence time, low ash carry over, high carbon conversion and low gas velocity [Puig-Arnavat *et al*, 2010]. Figure 2.7 shows the classification of fixed bed gasifier based on the flow direction of the oxidizing agent.

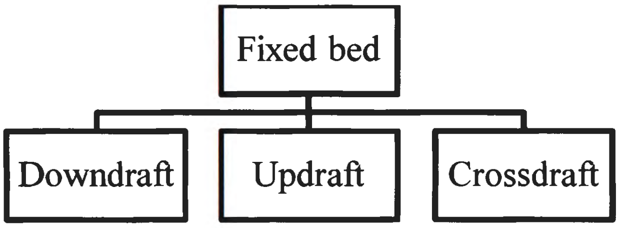

Figure 2.7: Classifications of fixed bed gasifiers

2.4 DOWNDRAFT GASIFIER

Downdraft gasifiers similar to other classes of gasifier consist of drying, pyrolysis, reduction and oxidation zone whose heights are of significance in gasification process and in obtaining a producer gas of high quality. According to Sheth and Babu [2009] report, the conversion of CO_2 produced in the combustion zone to CO is dependent not only on rate of reaction in the reduction zone but also on the height of reduction zone. Furthermore Jayah *et al* [2003] established an increasing trend in conversion efficiency as the gasification zone length increased for three different particle sizes.

Downdraft gasifiers generally have an advantage of producing gas with low tar concentration, which makes them suitable for operating gas engines and turbines used for electricity generation. The concentration of tar in the producer gas generated from a downdraft gasifier is relatively low when compared to that from updraft gasifier. It ranges between 10 and 100 g/Nm^3 for downdraft gasifier and 50 and 500 g/Nm^3 for updraft gasifier [Martinez *et al*, 2012].

Two types of downdraft gasifier exist; they are Imbert and stratified downdraft gasifier. Imbert downdraft gasifier also known as throated downdraft consists of a throated combustion zone where the decomposition of tar into non-condensable gases takes place. Figure 2.8 shows the schematic diagram of an Imbert downdraft gasifier.

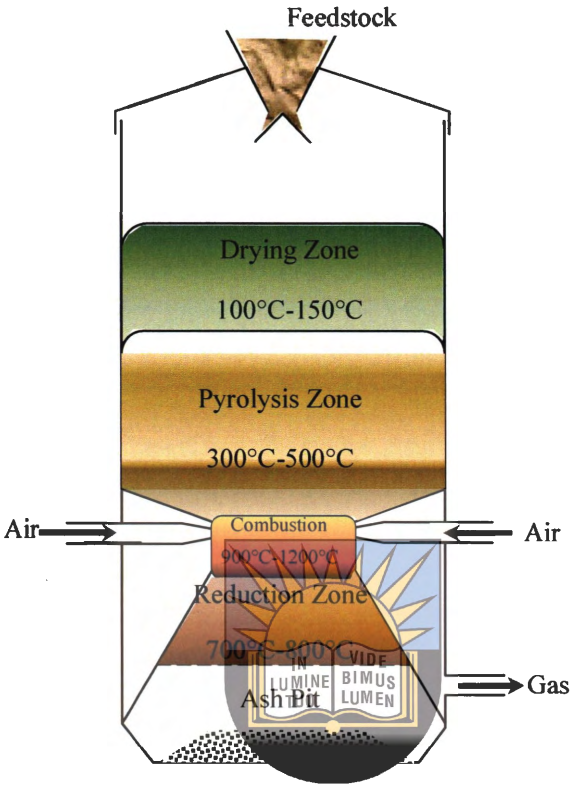

Figure 2.8: Diagram of an Imbert downdraft gasifier [Reed and Das, 1988]

The location of air nozzle just above the throat helps in maintaining a uniform temperature in the throat zone most especially in a small scale gasifier. Low temperature zone begins to surface with an increase in the reactor diameter which in turn increases the tar content of the producer gas generated. This is why this type of gasifier is limited to small scale. The difficulty in achieving a uniform distribution of air in larger scales is a limitation. Besides the difficulty of scaling up this type of gasifier, downdraft gasifier has a maximum allowable moisture content of about 40 % on a dry basis [Sheth and Babu, 2009].

The presence of throat in downdraft gasifier makes it less tolerant of particle size. Therefore it is recommended from literature that the particle size should be one-eighth of the throat diameter

[Martinez *et al*, 2012]. According to Chopra and Jain [2007] Imbert downdraft gasifiers are mostly used for gasification of woody biomass because of easy flow of such material through the throat, but results in formation of bridges when used for gasification of biomass with low density. However Imbert gasifiers have gone through some modifications which now allow them to accommodate biomass of both low and medium density fuel.

The problem of bridging and channeling led to the development of stratified or open top downdraft gasifier [Chopra and Jain, 2007]. Figure 2.9 shows the schematic diagram of a stratified downdraft gasifier.

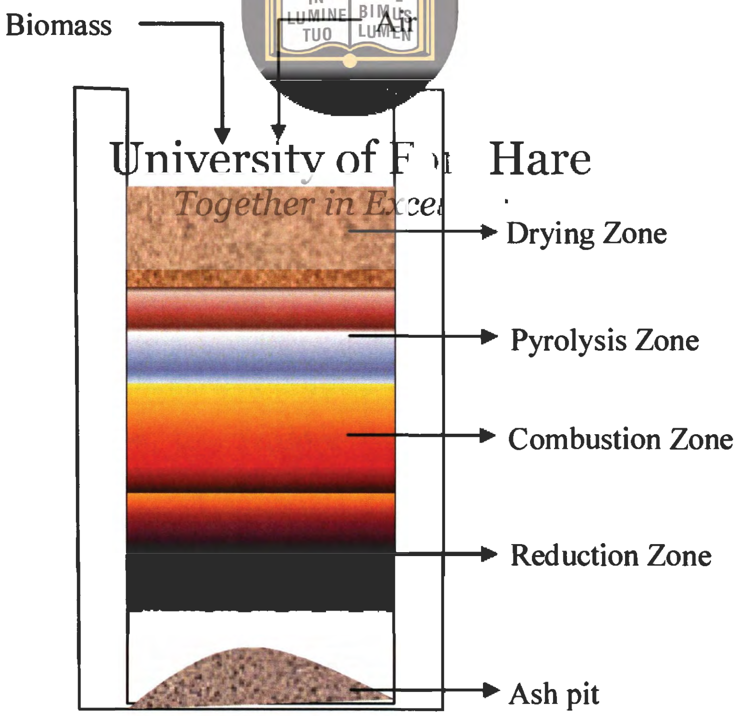

Figure 2.9: Stratified downdraft gasifier [Reed and Das, 1988]

Contrarily to Imbert, stratified downdraft gasifier has a uniform diameter all through the gasifier. The open top, which this type of gasifier possesses, enables a uniform flow of air down through the gasifier. This uniformity in flow of air hinders the formation of bridges and cold spot; therefore it ensures efficient conversion of biomass particles in the gasifier [Martinez *et al*, 2012].

Generally in a downdraft gasifier both the producer gas and the fuel (biomass particle) move downwards through the reactor. As the fuel particles are fed into the reactor they get oxidized at the oxidation zone and release heat. This heat is transferred to the drying and the pyrolysis zone where the biomass particles get dried and decompose into volatiles and charcoal. The quantity of energy that the particles are able to accumulate and the size of the particles determine the extent to which the volatiles are released. The released moisture and pyrolysis product all move downwards through the reactor, in the process some of the volatiles get condensed with the fuel particles and form tar. These tars get cracked in the oxidation/combustion zone because of the existence of high temperature. More also some other reactions listed in table 2.1 occur in this zone as well. Finally, the resulting gas mixture passes through a bed of hot charcoal supported by a grate [Sheth and Babu, 2009]. The producer gas then exits through the gas outlet located below the grate high temperature (about 700-800°C) thus leading to lower overall efficiency.

Despite the low concentration of tar in the producer gas generated in a downdraft gasifier the gas still needs to undergo further cleaning so as to obtain the desired gas quality. Patil *et al* [2011] obtained an average tar content value of 48 g/Nm^3 in the producer gas generated. While Dorgu *et al* [2002] obtained an average tar content of 3 g/Nm^3 and 6.3 g/Nm^3 in the gasification of hazelnut and sewage sludge in a downdraft gasifier respectively. In comparison Patil *et al* [2011] concluded that the disparity in the tar content was mainly due to the throatless nature of the downdraft gasifier used in their study unlike the throated type used by Dorgu *et al* [2002]. This brings to light the significance of downdraft gasifier design features. Besides its influence on tar formation, gasifier design also influence conversion efficiency. Increasing the length of the reactor leads to an increased operational efficiency, this is because of the long residence time it avails for sufficient conversion of biomass to take place [Martinez *et al*, 2012].

Dogru *et al* [2002] investigated the gasification characteristics of hazelnut shell using a pilot scale downdraft gasifier with 5 kW electrical outputs. It was suggested that the gasifier should be operated at an optimum air fuel ratio of 1.37-1.47 Nm^3/kg and biomass feed rate of 4.02 – 4.70 kg/h for a high quality combustible gas to be obtained. This suggestion was as a result of higher gross calorific value of 4.75–5.19 MJ/Nm^3 that was obtained within these ranges.

Jayah *et al* [2003] calibrated a computer program from an experimental result in order to investigate the impact of some operating and design parameters on conversion efficiency of a downdraft gasifier. The operating parameters were moisture content, particle size and inlet air temperature and the design parameters were throat angle and heat loss. Table 2.2 shows the summary of the result obtained in this study. Air inlet temperature was excluded from the table because its influence was considered to be negligible.

Table 1.2: Comparison of gasification efficiency with length of gasification zone [Jayah *et al*, 2003]

Parameters	Efficiency at 22 cm gasification length	Optimum gasification length (cm)	Efficiency at optimum gasification length
Chip size			
1	57.2	24	57.3
3	56.0	32	56.3
5	54.7	33	55.2
Moisture content			
0	57.8	31	58.1
15	56.0	32	56.3
30	54.2	35	54.5
Heat loss			
5	73.8	29	74.4
10	62.8	28	63.2
15	51.5	25	51.7
Throat angle			
30	56.6	28	57.4
60	56.0	24	56.2
90	55.1	19	55.1

The increasing trend in conversion efficiency as particle size decreases as seen from the table is due to the more likelihood of smaller particles getting converted to gases faster than larger particles. Among these parameters investigated heat loss had the greatest effect on conversion efficiency. A greater percentage of the heat lost was attributed to the insulating properties of the gasifier and lesser percentage to generated tar. The last which is throat angle is a specific feature for downdraft gasifiers. Increasing the throat angle comes with a divergent effect that decreases the gasifier temperature and thus the reaction rate. Note that for optimum efficiency to be achieved at a smaller throat angle, the gasification length needs to be increased [Jayah *et al*, 2003]. In summary the design features of a downdraft gasifier is an important influential parameter that needs to be enhanced so as to achieve optimum operating conditions.

2.5 OPERATING PARAMETERS

Gasification operating parameters are those series of parameters that should be optimized during gasification so as to obtain a product gas with less or no amount of impurities and high calorific value. These operating parameters have a strong influence on the output parameters of a biomass gasifier. In a fixed bed gasifier some of the output parameters influenced include gasification efficiency, producer gas composition, gas yield and calorific value of the gas produced. The critical operating parameters include the gasification agent, equivalence ratio, temperature of input air as well as gasifier operating temperature.

2.5.1 Oxidizing agent/ gasification agent

Air, steam and oxygen or a mixture of them are the most common oxidizing agent for gasification processes. The choice of any is based not only on the end use application of the product gas but also on the gasification technology employed and economic factors. Air is the most common among them because it is cheap and readily available. The use of air as an oxidizing agent results in syngas with low calorific value (CV) of about 4-7 MJ/Nm^3. This is due to the high concentration of nitrogen that air introduces [Holmgren *et al*, 2012]. Besides calorific values, oxidizing agents also influence the compositions of the syngas.

According to Martinez *et al* [2012] air gasification in a downdraft gasifier resulted in a syngas with the following composition: 15-20% of H_2, 15-20% of CO, 0.5-2% of CH_4, 10-15% of CO_2 and the remaining being N_2, O_2 and C_xH_y. Contrary to air gasification, steam and oxygen gasification yields syngas with a medium calorific value of about 12-18 MJ/Nm^3. Additionally, the use of steam and oxygen as oxidizing agents increases the concentration of combustible gases and reduces that of non-flammable gases such as nitrogen. However the generation of oxygen and steam incurs additional costs due to their energy requirements. This raises the cost of using both as oxidizing agents thereby limiting their usage/application. In terms of hydrogen production steam and oxygen gasification gives a higher yield when compared to air gasification. This is in accordance with Zou *et al* [2012] experimental demonstration where a steam to biomass ratio of 1.2 yielded 35% of H_2 and 12% of CO.

2.5.2 Equivalence ratio

Equivalence ratio (ER) often referred as fuel to air ratio is one of the governing parameters during gasification of biomass. It is defined as the ratio of the actual volume of air or oxygen required for the gasification of a particular kilogram of biomass fuel to the volume required for stoichiometric combustion of the same kilogram of fuel. The rate at which biomass are consumed in a downdraft gasifier is determined by the amount of air or oxygen fed into the gasifier [Martinez *et al*, 2012]. The suitable value for equivalent ratio ranges from 0.2-0.4. The aim of gasifying within this range is to obtain a product gas that is suitable for electricity generation, transportation fuel and other applications bearing in mind that equivalence ratio affects the quality of syngas [Martinez *et al*, 2012].

Increase in equivalence ratio results in an increase in gasification temperature and also leads to a higher yield of H_2 and CO. An experimental investigation of a downdraft biomass gasifier by Zainal *et al* [2002] showed the percentage compositions of the resulting producer gas at different equivalence ratio. In this study the percentage of H_2 increased linearly with increase in equivalence ratio but CO increased up till an equivalence ratio of about 0.38 and then started decreasing but not linearly. CO_2 did the opposite, it first decreased with an increase in equivalent ratio, but at about 0.35 equivalence ratio the trend changed, CO_2 started increasing.

More also an increase in equivalence ratio caused a rise in the calorific value of the gas up till an equivalence ratio of 0.388 before it started decreasing. Figure 2.10 shows the influence of equivalence ratio (air factor) on gas heating/calorific value [Van den Enden and Lora, 2004].

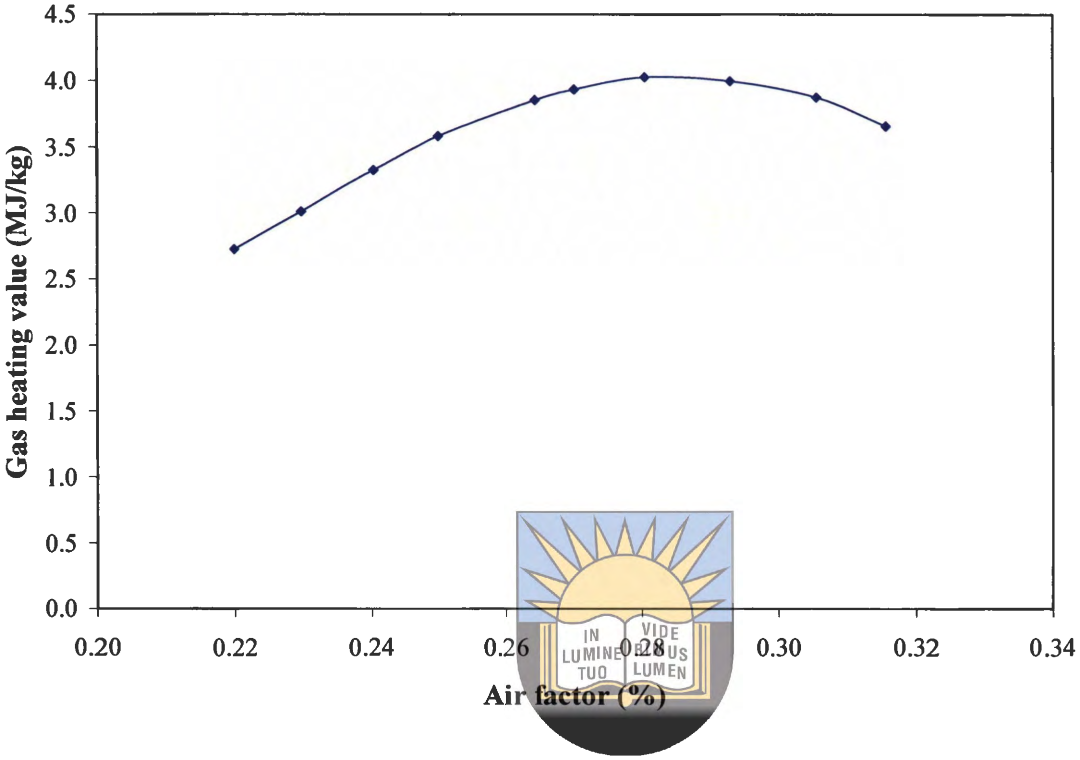

Figure 2.10: The dependency of calorific or heating value of gas on equivalence ratio [Van den Enden and Lora, 2004]

The best heating value of the gas was obtained at an air factor (equivalence ratio) of about 0.285. Beyond this point the nitrogen content of the air started diluting this gas and hence caused a decrease in the heating value. Some other parameters affected in Zainal *et al* [2002] study were cold gas efficiency and mass conversion efficiency. Table 2.3 provides a summary of these parameters

Table 2.3: Effect of equivalence ratio on some selected parameters [Zainal *et al*, 2002]

Equivalence ratio	Cold gas efficiency	Mass conversion efficiency	Type of biomass
0.259	68.37	98.39	Wood chip
0.268	67.65	98.83	Wood chip
0.287	76.68	90.12	Wood chip

With the few data shown in table 2.3 one can't conclude what effect a further increase in equivalence ratio will have on both parameters. But according to Wang *et al* [2007] an increase in equivalence ratio from 0.16 to 0.26 caused a rise in cold gas efficiency from 57 % to 74 %. Figure 2.11 further illustrates the dependency of cold gas efficiency on equivalence ratio.

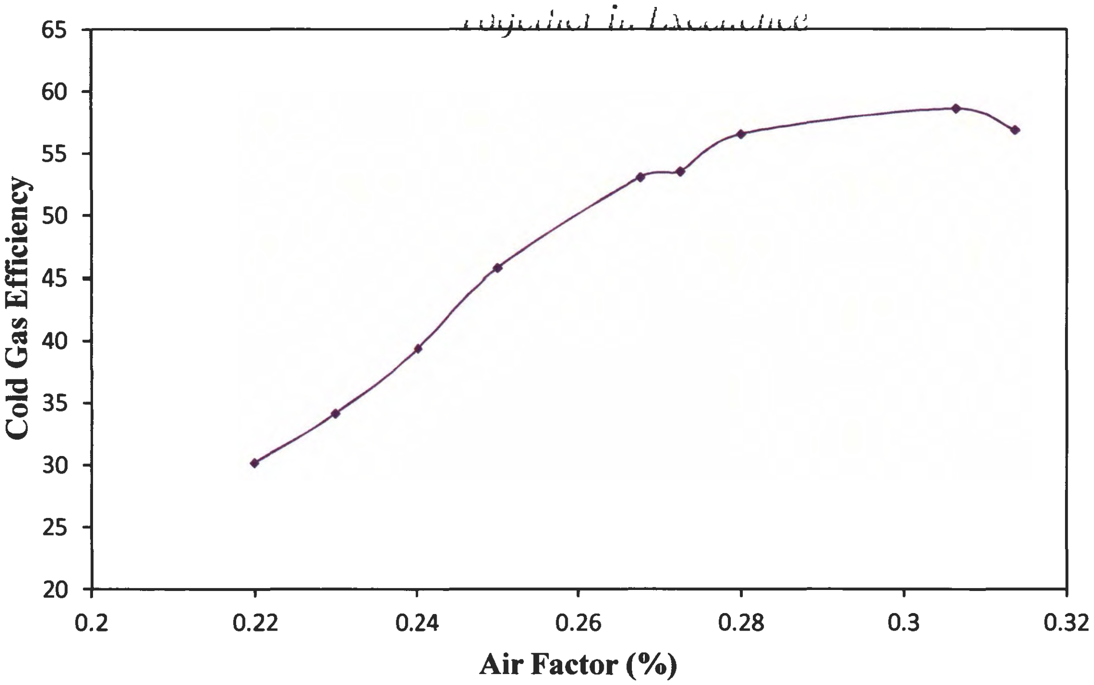

Figure 2.11: Cold gas efficiency with air factor [Van den Enden and Lora, 2004]

An increase in air factor from 0.22 to about 0.3 in fig 2.11 led to more combustion of biomass which in turn resulted in an increase in efficiency. Besides cold gas efficiency, there was also an increase in higher heating value (HHV) and gas flow rate from 3.6 MJ/Nm^3 to 4.2 MJ/Nm^3 and from 41 Nm^3 to 46 Nm^3 respectively. H_2 and CO concentration experienced an increase as well from 8.5% to 13.9% for H_2 and 12.3% to 14% for CO [Wang *et al*, 2007].

A more recent study reported that there was a reduction in the molar fraction of N_2 and CO_2 as equivalence ratio rose from about 0.165 to 0.205 but at a higher value of equivalence ratio these non flammable gases started increasing. The opposite was the case for the molar fraction of H_2 and CO because they first increased before they started decreasing. At equivalence ratio of 0.17, cold gas efficiency was found to be 0.25 and this value almost doubled with a little increase in equivalence ratio of 0.035. Finally the producer gas production rate showed a steady increase with equivalence ratio increase and an optimum equivalence of 0.205 was obtained for the downdraft gasifier studied [Sheth and Babu, 2009].

2.5.3 Input air temperature and gasification temperature

Pre heating of air prior to gasification is beneficial in terms of conversion efficiency, heating value, gaseous product yield and quality. However, this process comes with additional energy requirement, thus incurring additional cost. For instance to raise the temperature of an ambient input air of 50 kg/h from 300°C to 450°C would require an energy of about 2 kWh and this temperature increment could only lead to a slight increase in conversion efficiency (0.5%) [Jayah *et al*, 2003].

In another study as the air temperature used in the gasification of wood pellet of size 12 mm increased from 350°C to 830°C the combustible gaseous components also experienced an increase. H_2 formation increased from 10.6% to 13.2%, this increase is due to the dominance of shift reaction (R9) between the temperature of 500°C and 600°C. Shift reaction being exothermic in nature causes an increase in gasifier temperature which favours production of H_2. The increased H_2 content through direct hydrogenation resulted in more production of methane from 3.2% to 4.2%. Increase in gasifier bed temperature which comes as a result of raising the air temperature favours boudouard reaction (R5) which produces CO. These increase in combustible gaseous components as a result of increase in air temperature (350°C to 830°C) when summed up resulted to a rise in the lower heating value of the fuel gas from 6.9 MJ/Nm^3 to 8.7 MJ/Nm^3 [Lucas *et al*, 2004]. More also, pre heated air enhances cracking of tars which in turn improves the quality of the gas produced [Raman and Ram, 2013].

Gasification temperature is another important operating parameter that influences the quality of syngas produced. The goal of most gasification research has been to improve the quality of syngas and carbon conversion efficiency. In a bid to achieve this goal many researchers have reviewed, modeled and conducted experiments on biomass gasification from different angles. From the point of view of temperature there is a great need to maintain the gasification temperature at a certain degree so as to keep the gasification reaction running as required [Ran and Li, 2012].

The composition of syngas produced is influenced by the temperature inside the gasifier and temperature in turn is influenced by equivalence ratio (air or oxygen ratio). Wang *et al* [2007] recorded a rise in temperature from 940°C to around 1100°C and from 730°C to 900°C at the bottom of the gasifier as equivalence ratio (gasification air ratio) rose from 0.16 to around 0.27. Figure 2.12 shows the influence of equivalence ratio on gasification temperature [Mathieu and Dubisson, 2002]. Both cases showed an increase in temperature notwithstanding that different oxidizing agent was used.

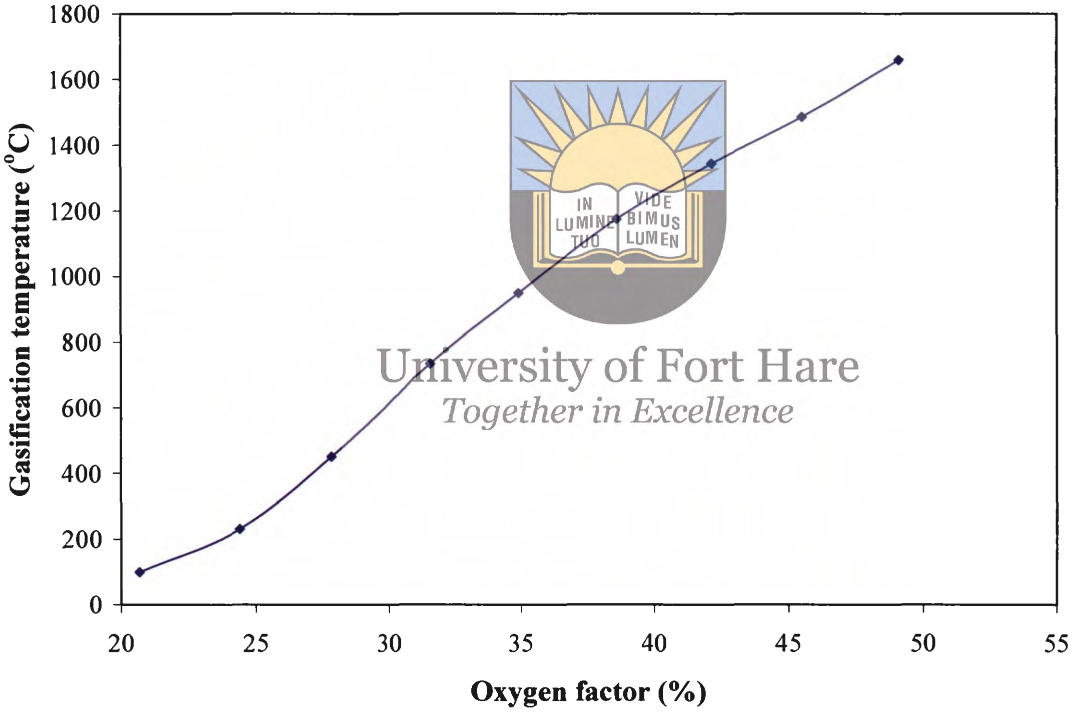

Figure 2.12: Effect of oxygen factor (equivalence ratio) on gasification temperature [Mathieu and Dubisson, 2002]

This rise in temperature is due to the fact that more char are combusted with increase in air or oxygen ratio. This implies that more of R1 and R2 are taking place in the gasifier and more energy is released in the process. The released energy raises the gasifier temperature and also promotes R5 and R6. This is the reason for the higher yield of H_2 and CO at high temperature. High concentration of H_2 and CO improves the quality of syngas and also determines its suitability for further application. At high temperature the amount of tar present in the syngas is greatly reduced as well, through cracking and this result in an increase in gas yield. This cracking of tar also increases the energy content of the product gas since some amount of energy are trapped in the tar. High temperature does not favour the production of CH_4 and CO_2 [Ruiz *et al*, 2013], more also based on the type of fuel and gasifier used could cause melting of ash which endangers effective operation of gasifiers. The maximum operating temperature of some gasifiers is limited by the ash melting point of the fuel [Siedlecki and De Jong, 2011].

Sheth and Babu [2009] found that during the gasification of wood waste in a downdraft gasifier the oxidation zone and pyrolysis zone temperature varied from 900°C to 1050°C and 260°C to 550°C respectively. The maximum temperature at these two zones was attained at an equivalence ratio of 0.25, also at the same ratio the fraction of H_2 and CO was at maximum and CO_2 at minimum. This is why the study concluded that 0.25 was the optimum equivalence ratio. Dogru *et al* [2002] observed that the temperatures at the drying, pyrolysis and throat zone was at maximum values of 125°C, 566°C and 1206°C respectively within an air fuel ratio of 1.4 to 1.45. Additionally the highest gross calorific value of the gas was obtained at 1050°C throat temperature. Therefore it was concluded that the downdraft gasifier used in the study was at its optimum performance at this temperature.

Lv *et al* [2007] reported that during the gasification of eucalyptus wood using a downdraft gasifier, it took a shorter time for combustion and reduction zone to attain a high temperature than the drying and pyrolysis zone. This is partly because of the gasifier thermal inertia that needs to be overcome. This thermal inertia maintained a steady state temperature of 300ºC, 600ºC, 700-900ºC and 800ºC in the drying, pyrolysis, combustion and reduction zone respectively. The temperature profile obtained by Sharma [2009] showed that the highest temperature was obtained near the oxidation zone and that this temperature improved from 1115 K to 1168 K when the gas flow rate was increased from 7 g/s to 9 g/s.

High temperature gasification is a means of improving conversion efficiency, calorific value and composition of gases. Pre heating of air prior to gasification plays a role in achieving this, but this process comes with additional energy requirement. Increasing partial oxidation is another means, with it there will be need for even distribution of the heat generated in the gasifier so as to avoid the existence of low temperature zones which could lead to more production of tar.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In order to determine the suitability of biomass and its potential as an energy source a good understanding of its properties and characteristics are required. These characteristics influence the choice of a conversion technology, as most technologies are fuel specific. They differ for different species of biomass and also vary over a wide range. The most important of these properties which influences the thermal co[illegible]f biomass through gasification are as follows: [Quaak *et al*, 1999]

- Elemental compositions
- Moisture content
- Volatile matter content
- Fixed carbon content
- Ash content
- Calorific value
- Bulk density

These properties can be classified as physical, chemical and morphological properties. In determination of the later biomass properties two characterization techniques are usually employed namely proximate and ultimate analyses. This chapter discusses the proximate and ultimate analysis methods employed to determine the latter properties before gasification as well as the gasifier used and the methods employed to collect data to achieve the objectives of this research.

3.2 THERMO GRAVIMETRIC ANALYSIS

This is a means of monitoring the behavioural change in the chemical and physical properties of a biomass when subjected to a controlled temperature condition. It is a highly developed technique with many applications. Abdullah *et al.* [2010] have used it to observe the pyrolytic behaviour and gas production profile of four lignocellulosic biomass material namely oil palm shell, oil palm frond, rice husk and paddy straw. In this study it was mentioned that thermo gravimetric analysis (TGA) can be useful in determination of the major components of biomass which are cellulose, hemicellulose and lignin. Due to difference in the chemical structures of these components their chemical reactivity also differs. Therefore knowing the quantities of these components in a biomass can give light in predicting the efficiency of its conversion [Carrier *et al*, 2011].

It reveals valuable information such as reaction mechanism, thermal stability, kinetic parameters and phase transformation. More also, it has been established through thermo gravimetric analysis (TGA) that hemicellulose, cellulose and lignin content of biomass decomposes at the respective range of temperatures 250 – 300°C, 300 – 350°C and 300 – 500°C. The influence of lignin content during combustion is also determinable through this technique and its differentiation.

Garcia *et al*, [2013] identified thermo gravimetric study as an effective tool in terms of determining the proximate analysis of biomass. It is time saving when compared to the traditional methods usually employed and also reduces the quantity of sample used. This study highlighted the use of this effective tool in monitoring the melting behaviour of ashes as a way of determining the structural changes that occur in a solid fuel during thermal conversion. Sung and Seo [2009] used TGA in investigating the non-isothermal behavior of stem biomass of Nicotiana tabacum. Higher decomposition of this material occurred within a temperature range of 120-250°C and this was attributed to high content of volatile and simple sugar present in the bright stem. The thermo chemical properties of a corn stover and its reaction kinetics in an inert and oxidizing atmosphere were determined by Kumar *et al*, [2008] using TGA.

According to the latter authors thermo gravimetric analysis is a useful tool for thermal analysis; therefore TGA was used in this study to carry out the proximate analysis of eucalyptus wood before the actual gasification in the downdraft gasifier. Proximate analysis gives a full description of the characteristics of a biomass material and reveals the gross components of a biomass material such as volatile matter, fixed carbon and ash content.

3.2.1 Material Choice and Preparation

Eucalyptus wood was chosen as a feedstock for this study basically for two reasons; first the gasifier system used was designed specifically for eucalyptus wood gasification. Secondly, the availability of this material added to its usage. Before its use in the gasifier it was cut to a desired size of 7.5 by 6.8 by 4.3 cm and weighed with a bathroom scale to determine its mass. For the purpose of proximate and ultimate analysis and calorific value determination it was grinded into a powder and sieved to a particle size of 0.18-0.25 µm. Additionally the moisture content of the eucalyptus wood samples was measured using Mini 2000 moisture meter which measures the actual percentage moisture content of a material. It measures the moisture content of a material within the range of 6-90% and has a resolution of 1% for moisture content range of 6-25%.

3.2.2 Basic operation of thermo gravimetric analyzer

Figure 3.1 shows the schematic diagram of a thermo gravimetric analyzer [Anandhan, 2001]. It consists of a sample pan which is usually a platinum or alumina crucible which holds the sample under analysis. In some cases an auto sampler that accommodates multiples of samples and automatically loads and unloads the sample is used. This sample pan is supported by a precision balance that monitors precisely the mass or weight of the sample during the experiment (analysis). The furnace houses the sample pan containing the sample and heats the sample with energy absorbed from the heat source which could be a halogen lamp. The temperatures of the sample and furnace are then measured with a thermocouple.

To maintain the required atmosphere the furnace is usually enclosed and an inert or non-reactive gas is allowed to flow in and over the sample and finally exits through the exhaust. Then the measured temperatures and weight are fed into the data acquisition system which can also be a computer system.

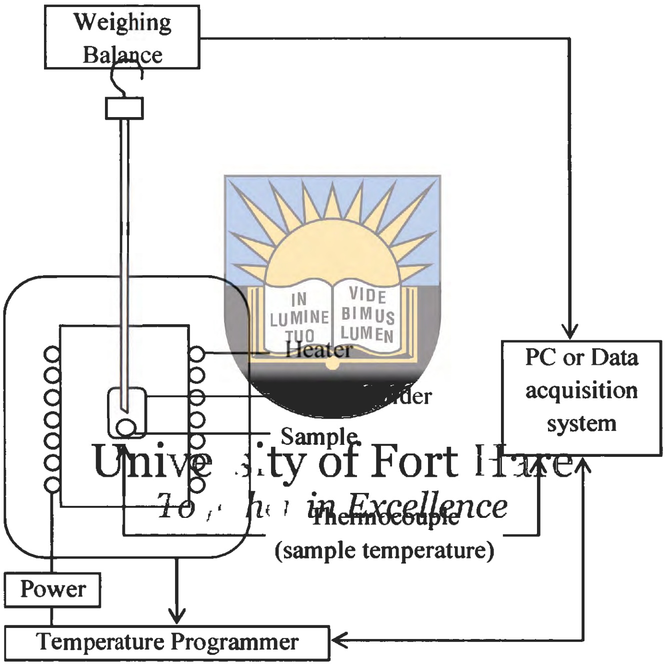

Figure 3.1 Schematic diagram of a thermo gravimetric analyzer [Adapted from Mackenzie, 1979].

3.3 ELEMENTAL COMPOSITION

This is one of the most important properties of biomass that determines its clean and efficient utilization. Furthermore it defines the energy content of a biomass material [Parikh *et al*, 2007]. Hence it is essential for determining the calorific value of a biomass material especially its carbon, hydrogen, oxygen, nitrogen and sulfur content. Elemental composition of biomass gives an idea of the potential pollution problems its combustion can cause. For instance, high composition of sulfur and nitrogen can lead to formation of acid rain during combustion of biomass [Quaak *et al*, 1999]. However these two elements are usually present in a small proportion especially in wood. The fractional composition of these elements can be quantified using ultimate analysis, which require specialized instrumentation and as a result are performed in specialized laboratories [Shen *et al*, 2010].

For the purpose of the present study a Carbon hydrogen nitrogen sulfur (CHNS) elemental analyzer was used in determination of the elemental composition of eucalyptus wood before feeding into the gasifier. CHNS analyzer has a wide range of applications; besides its use in energy it is also applicable in such fields as pharmaceuticals, polymers, environment, and food. This instrument comes in a modular form which gives room for its different configuration in order to suit specific applications [Thompson, 2008].

Carbon hydrogen nitrogen sulfur (CHNS) analyzer consists of a combustion section where a rapid combustion of the prepared sample occurs at a temperature of about 1000°C in a pure oxygen atmosphere. A pure copper metal is usually embedded beneath this section or in some cases in a separate furnace. During the combustion process carbon is converted to carbon dioxide, hydrogen to water, nitrogen to nitrogen gas/oxides of nitrogen and sulfur to sulfur dioxides. At the end of this conversion the inert gas (usually helium) sweeps the resulting product over the earlier mentioned copper heated at a temperature of about 600°C. This copper metal plays a dual role, it removes the oxygen that was not fully combusted and converts the oxides of nitrogen to nitrogen gas. Also embedded within the analyzer is the detection system which comprises of a gas chromatography (GC) column used for separation of the combustion gases and the thermal conductivity detector which quantifies the element. Figure 3.2 shows the schematic diagram of a CHNS analyzer.

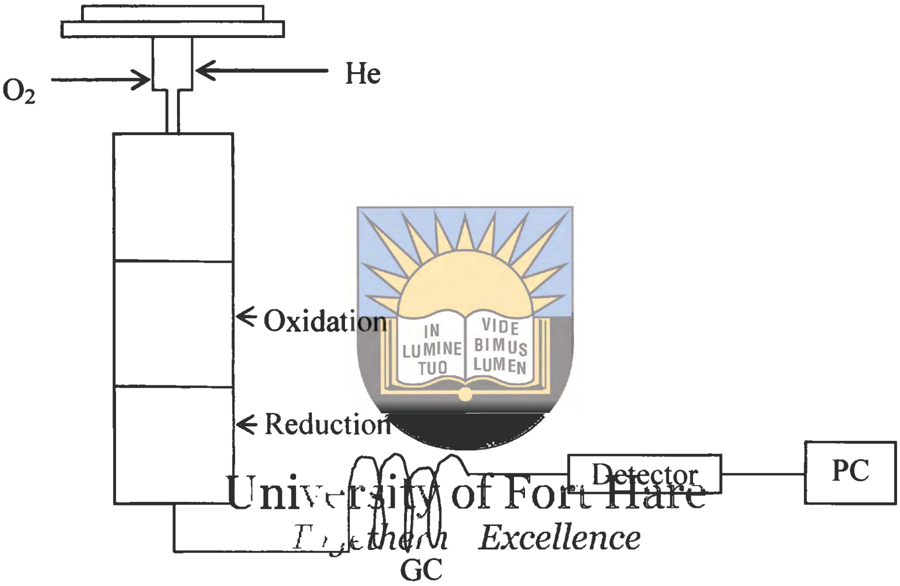

Fig 3.2 CHNS Analyzer Schematics [Adapted from Thompson, 2008]

CHNS analyzers usually exhibit two combustion modes namely: static and dynamic. In the static mode a set volume of oxygen is introduced into the combustion chamber prior to introduction of the sample while in dynamic, oxygen is introduced alongside with sample and afterwards a continuous flow of oxygen is allowed into the combustion chamber for a set time. The preparation of the sample to be analyzed is dependent on the sample type. Lastly the resulting ash which comprises of the inorganic residues and the remains of the tin after the combustion is usually collected in a ceramic crucible.

3.4 CALORIFIC VALUE DETERMINATION

The calorific value of a biomass reveals the amount of energy chemically bound in a material, which upon combustion is converted to heat energy [Erol *et al*, 2010]. Figure 3.3 shows Cal 2k ECO calorimeter employed in determination of the calorific value of eucalyptus wood [Cal 2K Digital data system].

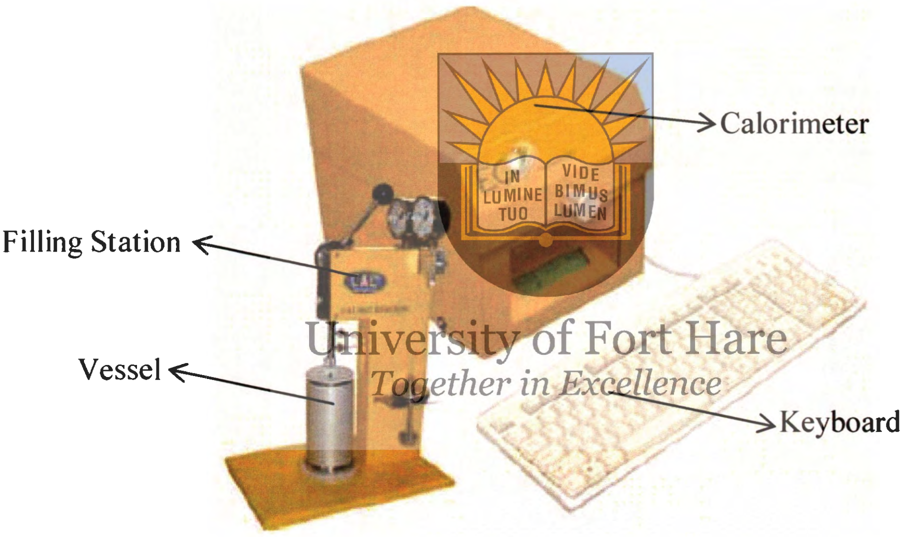

Figure 3.3: Components of the CAL-2K oxygen bomb calorimeter used for energy value determination.

This ECO system consists of a calorimeter, vessel, filling station and keyboard. The calorimeter can either be operated via a personal computer (PC) or as a standalone unit. A sample of the eucalyptus wood was weighed using measuring balance and placed in a crucible hung to the lid of the vessel. The vessel was then pressurized to 300 kPa using oxygen gas via the filling station before inserting it into the calorimeter. The mass of the sample which is 1g was entered using the keyboard. On closing the calorimeter lid the firing process was initiated and it took about 15 minutes for the firing process to complete. At the end of the firing, the calorific value was displayed on the liquid crystal display (LCD) and the resulting ash was kept in case it would be needed for further analysis.

3.5 DOWNDRAFT GASIFIER SYSTEM OPERATION

3.5.1 The System components and operation

The Johansson biomass gasifier system was installed with the aim of providing low cost electricity so as to improve the socio economic status of the community through establishment of small business that can be powered by the electricity produced [Mamphweli and Meyer, 2012]. Figure 3.4 represents the different components of Johansson biomass gasifier system. This system comprises of the reactor/gasifier, cyclone, scrubber, sawdust filter, safety filter, condensate tank and electrical generator.

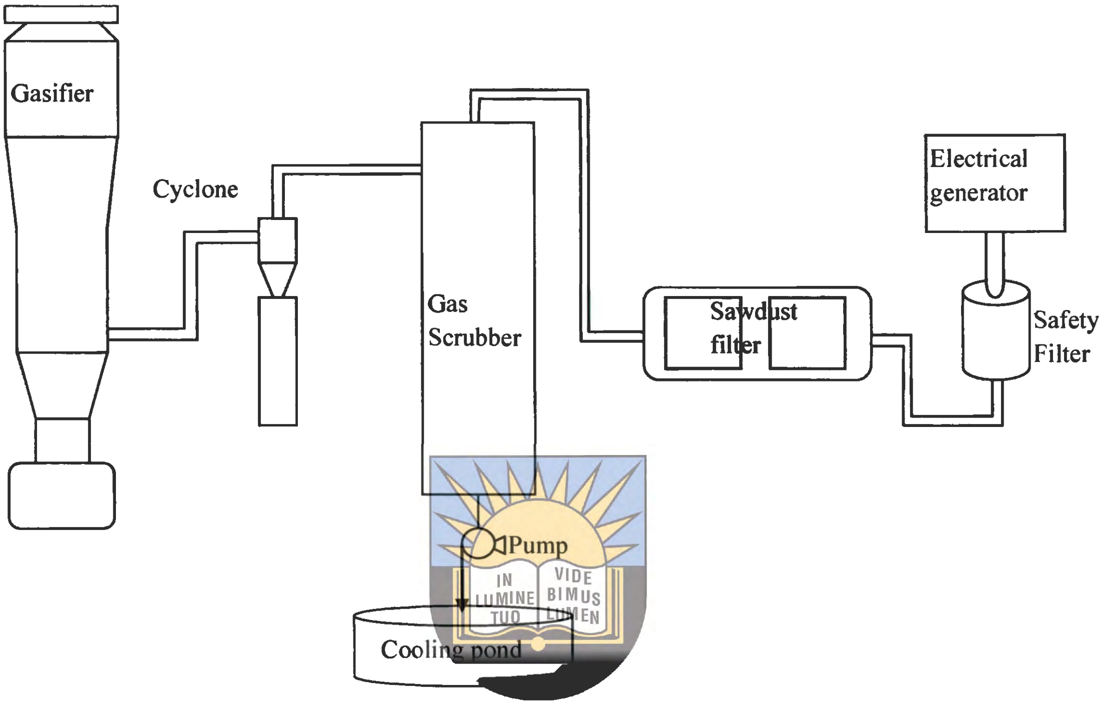

Figure 3.4: Schematic diagram of the Johansson biomass gasifier system

3.5.2 Reactor part of the System

The reactor consists of four zones corresponding to the four gasification processes namely: drying, pyrolysis, oxidation and reduction discussed in chapter two. Figure 3.5 shows a clear picture of the reactor used in this study.

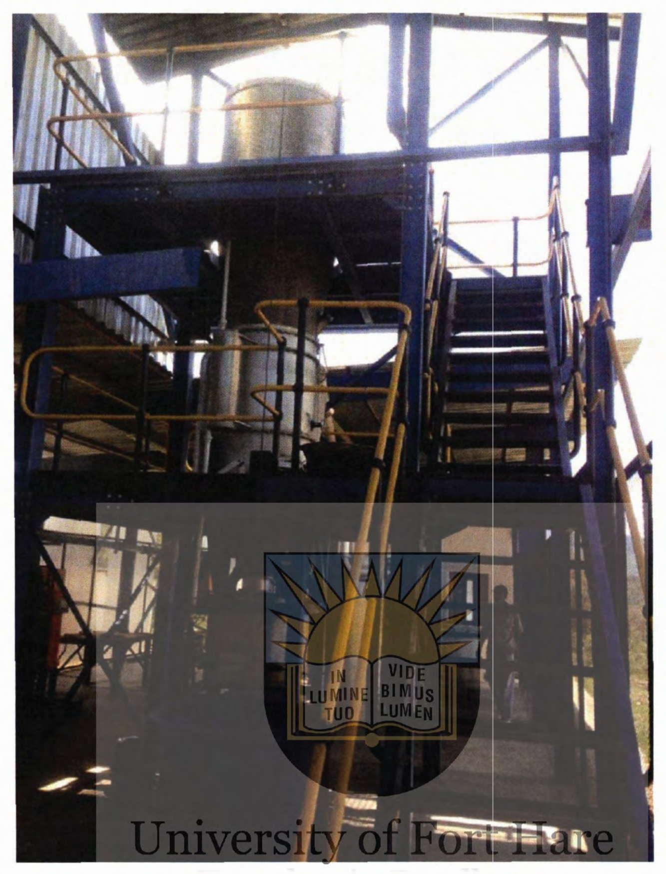

Figure 3.5: The reactor part of the system

The feedstock (eucalyptus wood) is fed into the gasifier hopper through the lid using an electrically powered winch. Air containing oxygen and some non-reactive gases such as nitrogen is blown into the oxidation zone through the air nozzles to start the combustion process. A 2 kW centrifugal blower is used to simulate the engine suction when igniting the gasifier. The gasifier is then ignited by inserting two or three party sparklers fitted in a sparkler holder through the ignition sleeve. Once combustion has started the oxygen content of the air reacts with solid carbonized fuel and hydrogen in the fuel as represented in equation 3.1 and 3.2 to produce carbon dioxide and steam respectively.

$$C + O_2 \rightarrow CO_2 \qquad -394\ \text{kJ/mol} \tag{3.1}$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \qquad -284\ \text{kJ/mol} \tag{3.2}$$

These exothermic reactions then provide the necessary heat that drives the other processes. For instance, in the reduction zone, the extent to which the endothermic reactions represented by equation 3.3-3.5 occur depends on the quantity of heat it receives from the oxidation zone. Furthermore this heat is used to drive off the moisture present in the eucalyptus wood at the drying zone [Barrio *et al*, 2007, Mamphweli and Meyer, 2012].

$$C + CO_2 \leftrightarrow 2CO \qquad +172\ \text{kJ/mol} \tag{3.3}$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad +131\ \text{kJ/mol} \tag{3.4}$$

$$C + 2H_2 \leftrightarrow CH_4 \qquad +74.8\ \text{kJ/mol} \tag{3.5}$$

The gas emanating from this zone (reduction) then goes through the gas purification system consisting of the cyclone, gas scrubber/cooler, particle interference/sawdust filters as well as the Donaldson 5 µm paper filter.

3.5.3 Purification units

3.5.3.1 Cyclone

The raw gas exiting through the bottom of the reactor first goes through the cyclone in a tangential manner. Here about 80 % of the coarse carbon particles and soot embedded in the raw gas are removed through centrifugal and inertia forces and exit through a pipe sealed by a rotary valve. The centrifugal force causes the particles to collide with the outer wall while moving downwards with the gas flow through inertia. At the bottom of the cyclone the gas flow reverses its direction and begins to move upwards. It then exits through a vortex finder at the top of the cyclone while the particles exit through the bottom. The particle collection efficiency of the cyclone depends on the size of the particles and the design of the cyclone as they come in different designs [Mamphweli and Meyer, 2012]. The gasifier system used is fitted with a conventional cyclone.

3.5.3.2 Gas Scrubber/ cooler

Figure 3.6 shows the gas scrubber/cooler of the 300 Nm^3 gasifier system at Melani village, Eastern Cape, South Africa.

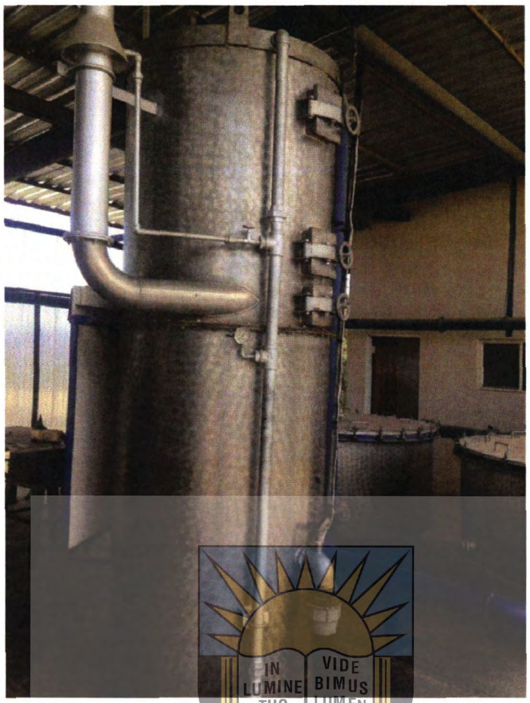

Figure 3.6: Picture of the gas scrubber/cooler

The hot gas from the cyclone enters the scrubber through the bottom at a temperature of about 500°C and exits through the top at room temperature (25°C). This loss of heat is undesirable in most applications especially where the sensible heat can be recycled and reused [Kumar *et al*, 2009]. The scrubber in addition removes the remaining fine carbon particles and soot in the gas that pass through the cyclone. This process washes off about 0.8 g/m^3 of gas which is translated to about 20% of the fine carbon particles. These particles (those less than 0.1 µm) are collected by diffusion when water is sprayed from the top of the scrubber while particles greater than 1 µm settle by gravity and are collected gravitationally, by impaction or by centrifugal means [Mamphweli and Meyer, 2012].

3.5.3.3 Sawdust and Safety filter/paper filter

The sawdust filter acts as a barrier and captures the very fine carbon particle that exits with the gas through the scrubber. The sawdust filters are filled with very fine sawdust that collects particles through adsorption. Lastly the clean gas passes through the safety filter, a double cartridge Donaldson air tight filter with a special gas tight seal between the dust bowl and the body of the filter. Figure 3.7 shows the picture of the two sawdust filters used.

Figure 3.7: Picture of the sawdust filters

3.5.4 Electric power generator

The electric power generator is a self excited three phase synchronous generator equipped with an automatic voltage regulator. This is an internal combustion gas engine, which was formerly operated on diesel but modified to operate on a 100% producer gas emanating from the gasifier. Figure 3.8 shows the gas engine that drives the 150 kVA synchronous generator.

Figure 3.8: The gas engine coupled to a 150 kVA generator

The three phase generator coupled to the producer gas engine has a capacity of 150 kVA, which works out to be 120 kWe power. It operates with a compression ratio of 14.5:1. Table 3.1 presents the details of the engine configuration.

Table 3.1: Configuration of the producer gas engine

Component	Detail/Units
Power output rating	120 kW
Compression ratio	14.5:1
Nominal bore	135 mm
Stroke	152 mm
Cubic capacity	2611 liters
Number of cylinder	12
Dry weight	2120 kg
Type of coolant	50% ethylene glycol and 50% water
Rated speed	1500 RPM

The electrical output of the generator was measured when powering a load bank connected to it. The load bank was constructed using twelve 12 kW water heating elements connected such that they draw maximum power from each of the three phases. Figure 3.9 shows an electrical circuit of the load bank designed using pspice software.

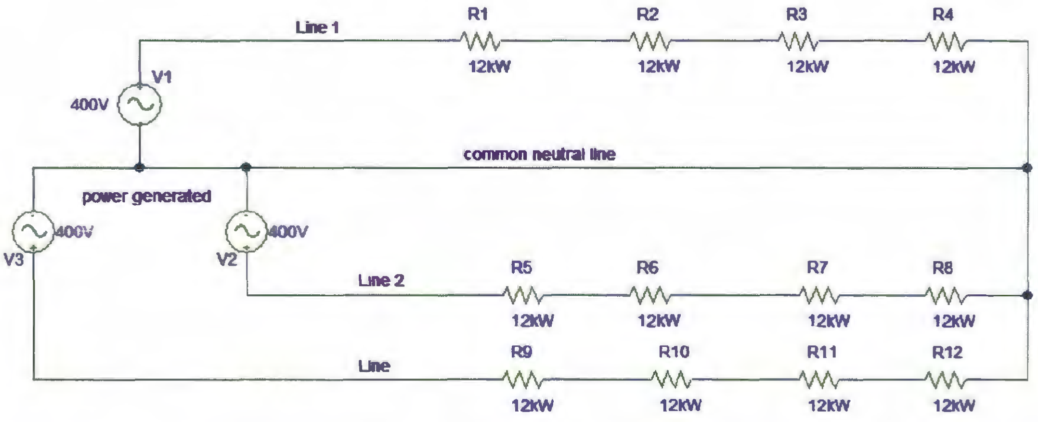

Figure 3.9: Schematic of the load bank circuit drawn using Pspice software

The electrical circuit in figure 3.9 represents the actual configuration of the load bank connected to the power sent out from the three phase generator. The power sent out from the constant 400 V line to line voltages arranged in star connection was at a desired frequency range of 50 - 55 Hz. It is depicted from the circuit that each line contained four 12kW heating elements connected in series (total power demanded by loads on each line is 48kW). The line current under the full load condition is ideally 120 A and the total power dissipated by the elements from the three lines is 144 kW. An energy meter was used to measure the current, voltage, power as well as energy from the generator during operation. Table 3.2 gives the specifications of the energy meter used.

Table 3.2: Basic specifications of the power meter

Specifications	
Power consumption	3.5 VA
Current probes supported	100 A clip-on
Measuring method	3 Watt/4Wire
Parameters measured	V, I, KW, KVA, KVar and power factor
Recording interval	1 minute
Communication interface	1xRS232 port
Accuracy	Class 1

3.6 GAS COMPOSITION AND TEMPERATURE DISTRIBUTION

Gas composition is an important output parameter in any gasification process. This parameter is influenced by a number of factors of which gasifier temperature is the most significant. Gasifier temperature profile reveals the manner in which heat is distributed and transferred and also the nature of chemical reaction occurring in the different zones of the gasifier. The custom built Gas and Temperature Profiling System (GTPS) was used in determining the composition of the gas emanating from the gasification of eucalyptus wood in the 300 Nm^3/h downdraft gasifier described earlier. Usually bulky and expensive equipment such as gas chromatography that require specialized facilities to operate are used for this purpose. The reliability of measurements realized from the GTPS has been confirmed [Mamphweli and Meyer 2013]. This study compared the result obtained from the GTPS with those from a gas chromatography, computer simulations and literature review. The results established an insignificant variation. Figure 3.10 shows the Gas and Temperature Profiling System.

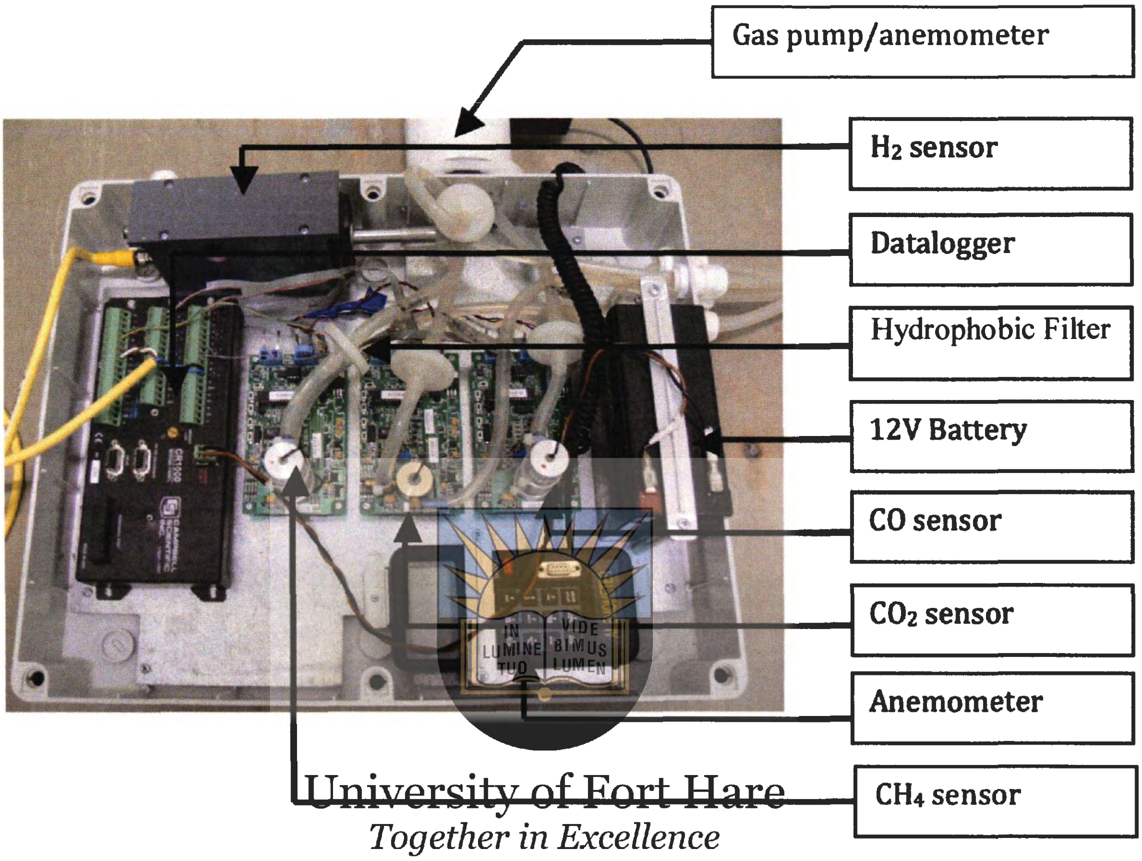

Figure 3.10: Gas and Temperature Profiling System [Mamphweli and Meyer, 2013]

The GTPS consist of three Non Dispersive Infrared (NDIR) gas sensors, one Palladium/Nickel (Pd/Ni) gas sensor, eight type K thermocouples, a CR1000 data logger, and a 12V battery. The gas sensors and the thermocouples are all connected to the data logger and the battery powers the whole system. NDIR gas sensor measures the concentration of carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) based on their energy absorption characteristics in an infrared region. The NDIR gas sensor consist of a gas cell (sample path) usually made in a tube like form with inlet and outlet port for easy penetration of light and interaction with the sample gas [Mamphweli and Meyer, 2013]. In the cause of this interaction the sample gas absorbs some amount of light which according to Lambert Beer law is directly proportional to the concentration of the gas.

$$A = \varepsilon cl \tag{3.6}$$

Where A is Absorbance, ε is molar absorptivity, c is the concentration of the sample, l is sample path length. Furthermore this gas concentration can also be determined from equation 3.8 bearing in mind that absorbance can as well be expressed as:

$$A = -\log \tau = \log \frac{I}{I_o} \tag{3.7}$$

$$I = Ie^{-\varepsilon cl} \tag{3.8}$$

Where τ is transmittance, I is transmitted intensity and I_o incident intensity. Further still, for a more accurate measurement an optical filter is fitted to the pyroelectric detector which allows only the absorption line of the gas of interest to be selected.

The Pd/Ni gas sensor detects the concentration of hydrogen (H_2) in the syngas via a thin film Pd/Ni alloy whose electrical resistance is a function of the absorbed hydrogen. This sensor measures hydrogen both in low and high ranges using a low level sensor such as metal oxide semiconductor capacitor with Pd/Ni plate and a high level sensor such as Pd/Ni thin film resistor respectively. The hydrogen detection occurs between a concentration of 0.1 and 100 % H_2 and at a temperature of 25°C. The measured parameters from the sensors and the thermocouples are stored in a CR1000 data logger, which consists of a central processing unit (CPU), analog and digital input and output and visual basic program for data processing and routine analysis. The stored data is then retrieved with PC400 software installed in a computer. Finally the accuracy and response of the system as a whole is mainly dependent on the accuracy of the gas sensors [Mamphweli and Meyer, 2013]. The gas calorific value was determined from the percentage composition of combustible gases as shown in equation 3.9

$$CV_{gas} = \left[\frac{(CO_{vol} \times CO_{HV}) + (H_{2vol} \times H_{2HV}) + (CH_{4vol} \times CH_{4HV})}{100} \right] \quad (3.9)$$

Where CO_{vol}, H_{2vol} and CH_{4vol} represents the volume concentration of carbon monoxide, hydrogen and methane present in the producer gas respectively. CO_{HV}, H_{2HV} and CH_{4HV} represent the heating value of these gases as stated in the standard gas table.

3.7 MASS BALANCE /ENERGY BALANCE AND EFFICIENCY DETERMINTION

The total weight of material (M_{in}) that entered the downdraft gasifier was estimated as follow

$$M_{in} = W_w + A_w \quad (3.10)$$

Where W_w is the weight of eucalyptus wood in kg that was consumed in the gasifier and A_w is the mass (kg) of air used. The total weight of output product P_{out} was also estimated as follows:

$$P_{out} = G_q + Ash + F_p \tag{3.11}$$

Where G_q and F_p are the total quantity of gas in kg and fine particles generated in kg respectively.

The energy balance of the downdraft gasifier was determined from total quantity of energy that went into the gasifier and the total quantity that came out as follows:

$$E_{in} = CV_{fuel} \times W_w \tag{3.12}$$

$$E_{out} = CV_{gas} \times G_q \tag{3.13}$$

Where E_{in} and E_{out} is the total input energy and output energy in MJ. CV_{fuel} is the calorific value of fuel in MJ/kg and CV_{gas} is the calorific value of producer gas in MJ/Nm^3.

The eucalyptus wood to producer gas conversion efficiency of the biomass downdraft gasifier was estimated as shown by Equation 3.14

$$CGE = \left[\frac{CV_{gas} \times W_w}{CV_{fuel} \times G_q}\right] \times 100\% \qquad (3.14)$$

The gas to power efficiency of the system was determined through equation 3.14 as follows

$$GPE = \left[\frac{El_{energy}}{E_{out}}\right] \times 100\% \qquad (3.15)$$

Where GPE represents gas to power efficiency and El_{energy} is the total electrical energy produced from the generator. Eucalyptus wood to electrical power production efficiency known as the overall efficiency of the system is given as:

$$WPE = \left[\frac{El_{energy}}{E_{in}}\right] \times 100\% \qquad (3.16)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 FEEDSTOCK ANALYSIS

Knowing the chemical and physical characteristics of the feedstock prior to gasification is necessary. The proximate and ultimate analysis of the eucalyptus wood was undertaken before the gasification of the material.

4.1.1 Elemental composition

Table 4.1 shows the carbon, hydrogen and nitrogen percentage composition of the eucalyptus wood obtained through carbon hydrogen nitrogen sulfur (CHNS) analyzer.

Table 4.1: Ultimate analysis of eucalyptus wood

Biomass	Ultimate analysis % by weight			
	C	H	N	O
Eucalyptus Wood	47.51	6.524	0.095	45.87

The composition of oxygen was determined by difference as follow [Bech *et al*, 2009].

$$O = 100 - \%C - \%H - \%N \qquad (4.1)$$

The letters O, C, H and N represents the compositions of oxygen, carbon, hydrogen and nitrogen respectively. Sulfur was not detected in the analysis probably because; the composition of sulfur in the material was too low to be detected by the analyzer.

The major compositions of eucalyptus wood were found to be carbon and oxygen, with carbon dominating oxygen by 1.64%, while the minor components were hydrogen and nitrogen. The minimal composition of nitrogen and absence of sulfur in the sample shows that the use of eucalyptus wood for gasification purposes poses no threat to the environment in terms of the gases emitted. The low composition of nitrogen in the wood would result in minimal emission of nitrogen oxides (NOx) and absence of sulfur indicates absence of sulfurdioxides. The percentage compositions of these elements, falls very well within the ranges obtained by other researchers [Jayah *et al*, 2003, Cuiping *et al*, 2004, Carrier *et al*, 2011].

4.1.2 Thermal analysis

The Thermo Gravimetric Analysis (TGA) was carried out both in isothermal and scanning mode. The former examined the change in mass of the sample as a function of time while the later examined mass change as a function of temperature. In the scanning mode the temperature was first held for 10mins at 37°C and then heated from 37°C to about 900°C with a nitrogen flow rate of 20ml/min. Figure 4.1 shows the TG (in % weight) and DTG (in % weight/°C) curve of eucalyptus wood used.

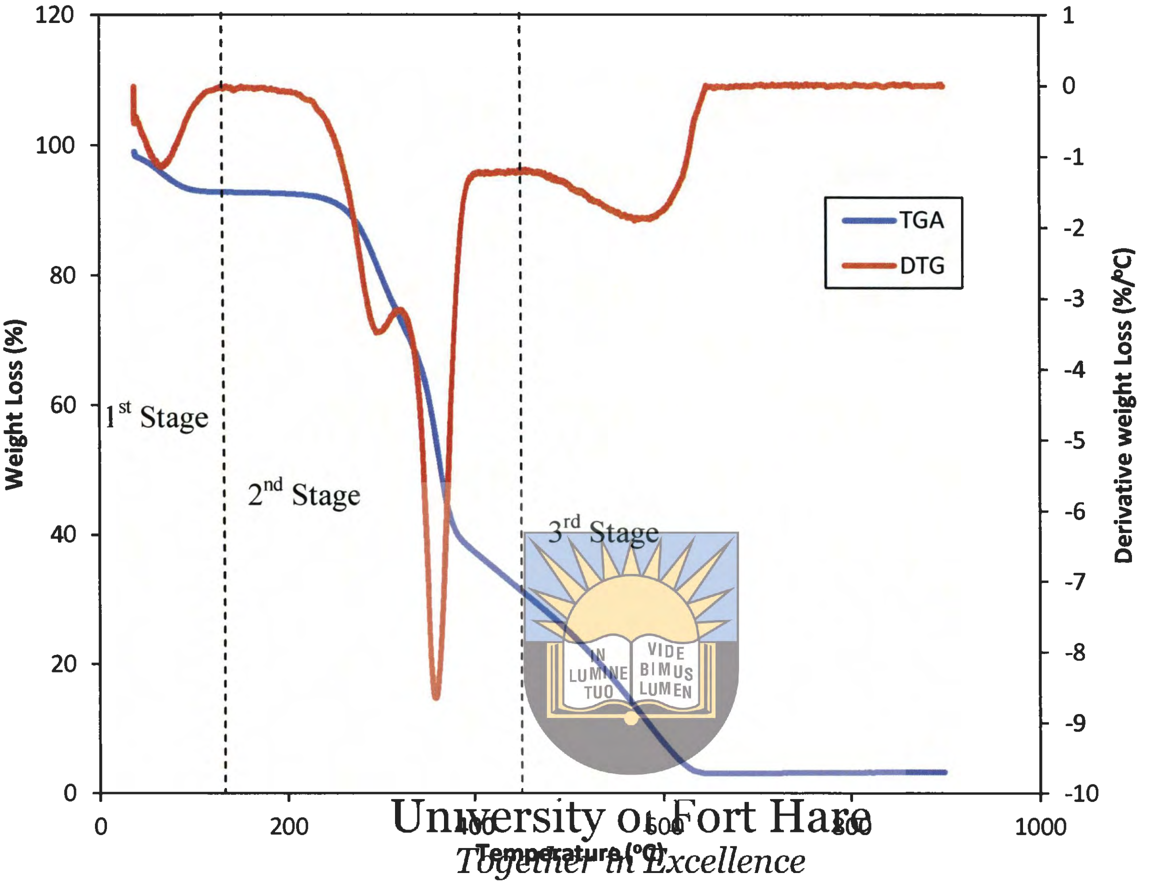

Figure 4.1: TGA and DTG curves of eucalyptus wood in scanning mode.

The TGA curve shows the instantaneous wood weight at specific temperatures as the temperature increases. As expected, temperature had a significant effect on the weight loss of the eucalyptus wood. The change in slope which can be divided into three stages corresponds to the transformation stages the eucalyptus wood went through in the TGA. The first stage which is between the temperature range of 37°C to about 120°C represent the evaporation of moisture from the eucalyptus wood. This is accompanied by a slight change in weight. The second stage accompanied by a significant weight loss is attributed to the degradation of cellulose, hemicellulose and some part of lignin. This degradation process resulted in the release of volatiles and it occurred between the temperature ranges of 200°C - 450°C. Beyond this stage, weight loss decreases until a constant weight is reached and this is attributed to further decomposition of the remaining part of lignin [Pasangulapati *et al*, 2012]

The DTG portrays the different reactions occurring over the entire temperature range. The peaks indicate the different degradation steps of the eucalyptus wood compositions. Table 4.2 shows the percentage compositions of these contents.

Table 4.2: Proximate analysis of eucalyptus wood sample

Biomass	Proximate analysis % by weight			
	Mositure Content	Volatile Matter	Fixed Carbon	Ash Content
Eucalyptus Wood	14	67.72	17.88	0.4

The 14% moisture content obtained from the proximate analysis fell within the required range for gasification especially in a downdraft gasifier. It implies then, that minimal amount of energy is required to evaporate the moisture during the gasification process thereby, reserving more energy for the reduction reactions and at the same time improve the overall energy balance of the biomass gasifier system.

The 67.72% of volatile matter obtained represents the proportion of the eucalyptus wood that was released as gas. This high volatile matter content (67.72%) indicates the presence of functional groups at a higher proportion than the aromatic structures in the eucalyptus wood material. It also signifies the ease with which the material can be ignited. Beside this positive contribution high volatile matter content has, it also leads to more production of tars during gasification process. However the tar free downdraft gasifier used in this study curbs this problem through cracking of the tars [Mamphweli and Meyer, 2009, Harun *et al*, 2009].

The fixed carbon represents the carbon content which does not decompose easily at low temperature. Low ash content minimizes the likelihood of slag formation at high temperature during the actual gasification.

4.1.3 Calorific value of the eucalyptus wood

Calorific value (heating value) reveals the amount of energy chemically bound in a solid fuel. It is a significant parameter in determining the energy balance of a biomass gasifier system. It can be determined via multiple routes; experimentally or through calculations (from proximate/ultimate analysis values). Experimentally a high heating value of 19MJ/kg was obtained for the eucalyptus wood used in this study. This was in agreement with the values obtainable for wood with less than 1% ash content [Werther et al, 2000 and Mckendry, 2002].

After deduction of the energy trapped in the water vapour, the heating value reduced to 16.34 MJ/kg. This value is usually referred to as the lower heating value. The lower heating value was further verified by fitting the proximate analysis data in table 4.2 into 13 new correlations (equations) developed by Erol *et al* [2010]. The best result (minimal error) was obtained from equation with the highest number of features shown below.

$$CV = -116 - 1.33[AC] - 0.005[VM] + 1.92[VM + AC] - 0.0227[VM * AC] - 0.0122[VM]^2 + 0.0299[AC]^2 + 6133[OM]^{-1} - 0.82[AC]^{-1} \tag{4.2}$$

The features CV, AC, VM, and OM represent calorific value, ash content, volatile matter and organic matter respectively. AC and VM are presented in table 4.2 whereas OM was determined by difference as shown.

$$OM = 100\% - AC \tag{4.3}$$

From equation 4.2 calorific value of the eucalyptus wood was estimated to be 16.89 MJ/kg which differed slightly from the actual value (16.34) measured. This value is within the known calorific value of wood. It is important to mention here that increase in ash content lowers calorific value of solid fuels. For instance every 1% increase in ash results in a 0.2 MJ/kg decrease in calorific value [McKendry, 2002, Mamphweli and Meyer 2009]. The calorific value of 6.34 MJ/kg was used to calculate the conversion efficiency of the gasifier system.

4.2 GASIFIER SYSTEM OPERATING PERFORMANCE

4.2.1 Gas Analysis

Gas analysis is of great important because it provides information such as percentage composition of gases, energy content of the gas as well as the quantity of gas produced. Figure 4.2 shows the profiles of the gases measured with the gas and temperature profiling system described in the methodology chapter. Gas production was allowed to stabilize before measurements were taken.

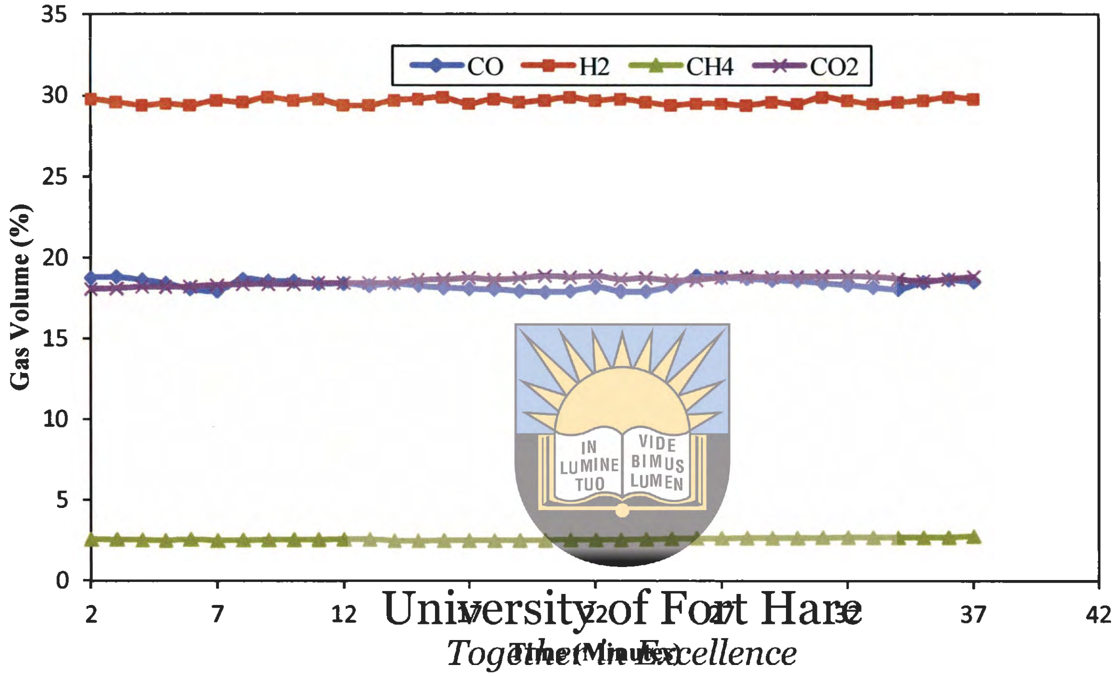

Figure 4.2: Percentage compositions of the producer gas

On average the percentage compositions of the gases are 29.6% of H_2, 18.4% of CO, 18.57% of CO_2 and 2.6% of CH_4. Nitrogen and other inert gases make up the remaining composition of the gas, which is relatively high. The high percentage of nitrogen is because it is an air blown gasifier. The fluctuation in the gases is due to the loads the gas engine powers. The rate of gas production depends on how much gas the gas engine requires from the gasifier, which depends on the engine/generator load. The calorific value of the producer gas was calculated from the combustible component of the gas using equation 3.8. The respective heating values of H_2, CO and CH_4 used were obtained from the standard gas table. Fig 4.3 shows the calorific value of the gas.

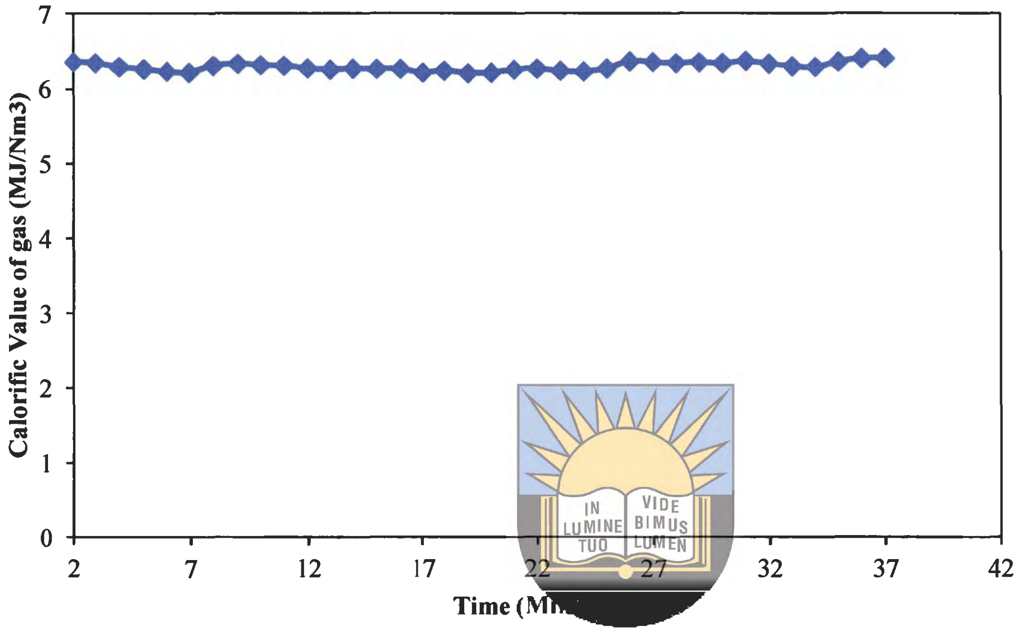

Figure 4.3: Calorific value of the producer gas

An average calorific value of 6.3 MJ/Nm^3 was obtained. This calorific value is within the range (4-7 MJ/Nm^3) reported for air gasification [Holmgren *et al*, 2012, and Martinez *et al* 2011]. This is attributed to the higher quantity of the combustible gases obtained in the present study as compared to the latter studies. The use of air introduces a higher quantity of nitrogen to the gas, which explains the reason for low calorific value of producer gas in general, when air is used as a gasification agent.

In addition the low heating value obtained in the present study could also be attributed to the low composition of methane in the gas, bearing in mind that CH_4 has the highest heating value compared to CO and H_2. This is why the heating value of natural gas is higher than that of syngas since it comprises more of CH_4. Besides gas composition, equivalence ratio also influences the calorific value of producer gas as will be discussed in section 4.2.3

4.2.2 Electrical Performance

The electrical output of the generator operated on a 100% producer gas was monitored using a power meter. During the operation of the generator the frequency varied between 50 Hz and 55 Hz. The current in the three phase when the engine was operated at full load (when the electrical demand from the engine is equal to the electrical output deliverable by the engine) varied between 104 A to 114A. The variation in cuurent occurred in the red and yellow phase while the blue phase remained constant at 107A. The voltage was fairly constant all through the operation of the engine. An average power of 121.93KW was obtained which is 1.93KW above the power rating of the engine. This implies that the gas supplied to the engine was able to drive the engine to its power rating.

4.2.3 Mass Balance of the System

The mass balance analysis was carried out to account for the materials that entered the gasifier and the product that came out. In total 718.64 kg of air was fed into the gasifier along side with 424 kg of eucalyptus wood. This worked out to be 63% of air and 37% of wood by mass fraction. Translating further showed that every 1 kg of the eucalyptus wood was gasified by 1.69 kg of air. This therefore corresponds to an equivalence ratio of 0.29 bearing in mind that on average 5.74 kg of air is required for complete combustion of 1 kg of wood. This equivalence ratio of 0.29 resulted in a gas calorific value (heating value) of 6.3 MJ/Nm^3 which is higher when compared to 4.6 MJ/Nm^3 obtained at an equivalence ratio of 0.4 by Martinez *et al*, 2011.

The obtained equivalence ratio (0.29) agrees well with the optimum equivalence ratio of 0.285 reported [Van den Enden and Lora, 2004]. At an equivalence ratio of 0.29 the nitrogen content of the air is minimal thus increasing the combustible gases which are the major constituent of producer gas calorific value. Above this optimum equivalence ratio, the non combustible gases experience an increase thus reducing the compositions of the combustible gases. This in turn reduces the calorific value of the gas produced and at the same time will have an effect on the cold gas efficiency. This agrees with the findings of Van den Enden and Lora [2004] reviewed in section 2.5.2 of chapter two. Equivalence ratio is an important gasification parameter that should be carefully monitored. Figure 4.4 shows an illustration of the mass balance of the system.

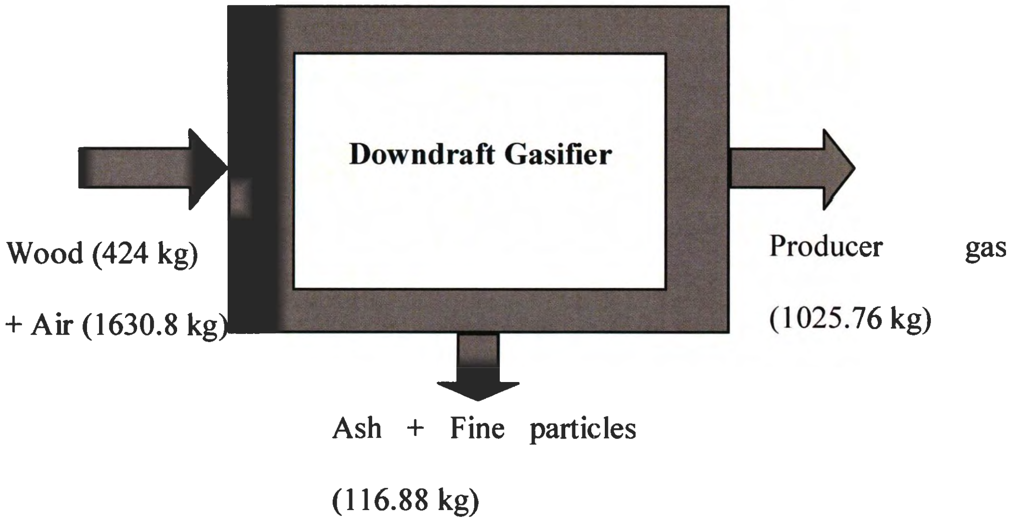

Figure 4.4: Schematic diagram for Mass balance of the system

The output product comprises of producer gas, ash and fine particles. Out of 1142.64 kg of input material 89.77% was converted to gas and the remaining percentage to ash and fine particles. Simplifying further showed that 1 kg of eucalyptus wood produced 2.29 Nm^3 of gas while consuming 1.69 kg of air. The obtained gas production rate (GPR) of 2.29 Nm^3 is slightly lower than the average value of 2.5 Nm^3 reported [Rajvanshi, 1986]. Table 4.3 presents the summary of the input material and output product for the mass balance analysis.

Table 4.3: Summary of mass balance analysis of the system

Input			Output		
Component	Unit(kg)	Mass fraction (%)	Component	Unit(kg)	Mass fraction (%)
Eucalyptus wood	424.00	37.00	Producer gas	1025.76	89.77
Air	718.64	63.00	Ash +Fine particles	116.88	10.23
Total	1142.64	100.00	Total	1142.64	100

4.2.4 Energy balance and efficiency determination of the system

The total energy input to the gasifier was estimated from the total kilogram of wood (424 kg) consumed and the calorific value of the wood (16.34 MJ/kg). This resulted in a total energy of 6928.16 MJ or 1924.49 KWh while the total energy output from the gasifier was estimated from the total quantity of gas (969 Nm^3) and heating value of the gas (6.3 MJ/Nm^3). This resulted in a total energy of 6104.7MJ or 1695.75 KWh. This therefore implies that 88.11% of the energy contained in the wood was converted to gas as shown in equation 3.7. The energy lost while converting wood to gas was then determined by difference and amounted to 11.9%. This loss is accounted for by the heat lost during the process of cooling the gas in the gas scrubber/cooler and through the gasifier walls.

The conversion efficiency of the system was evaluated in three stages: the first stage was from wood to producer gas, which was determined according to equation 3.14. This resulted in an efficiency of 88.11% generally referred as cold gas efficiency or gasification efficiency. Cold gas efficiency depends on the calorific value of gas and the quantity of gas generated as seen in equation 3.14. This efficiency obtained through this calculation is much higher when compared to about 60-70% reported for wood gasifiers [Rajvanshi, 1986]. This is attributed to the optimum equivalence ratio of 0.29 that the system was operated on which resulted in a higher calorific value than reported in other studies [Wang *et al*, 2007, Van den Enden and Lora 2004]

In the second stage, producer gas to electric power generation efficiency was evaluated based on the total electrical energy generated during the running of the system. The 150 kVA alternator coupled to the producer gas engine generated a total of 394.2 kWh of electrical energy from 969 Nm^3 of gas supplied to it. This then implies that 2.458 Nm^3 of gas was required to generate 1 kWh of electrical energy, resulting in a giving a producer gas to electric power efficiency of 23.2%.

Lastly the overall efficiency of the system was calculated from total fuel consumed in the gasifier and the electrical energy generated from the engine. A total of 424 kg of wood consumed resulted in a total electrical energy of 394.2 kWh. Hence, a specific fuel consumption rate of 1.075 kg/kWh and overall efficiency of 20.5% was obtained. This is approximately equal to the overall efficiency obtained for a dual fired downdraft gasifier system [Raman *et al*, 2013] but lower than that obtained in a two stage gasification system by 6% [Wang *et al*, 2007].

The specific fuel consumption rate of 1.075 kg/kWh obtained compares very closely to 1.1 kg/kWh reported by Raman *et al*, [2013] and 1.21 kg/kWh reported by Sridhar *et al* [2001]. The comparison to other studies presented in table 4.4 showed that lesser kilogram of wood is required by the system Johansson biomass gasifier to produce 1 kWh of electrical energy. This is an evidence of stable gasifier operating conditions, low ash turn over and low charcoal yield of the Johansson biomass gasifier system. Table 4.4 presents a summary of some performance parameters obtained and its comparison with literature.

Table 4.4: Comparing experimental data with literature

Biomass material	Optimum ER	CV_{gas} (MJ/Nm^3)	GPR (Nm^3/kg)	CGE (%)	Reference
Fuelwood	0.29	5.30	2.78	89.70	Raman *et al* (2013)
Furniture waste	0.205	6.34	1.62	56.87	Sheth and Babu (2009)
Wood chips	0.21	3.90	2.93	66.00	Wang *et al* (2007)
Hazel nutshell	0.276	5.15	2.73	80.91	Dogru *et al.* (2002)
Wood+ charcoal	0.388	5.62	1.08	33.72	Zainal *et al.* (2002)
Furniture waste	0.205	6.34	1.62	56.87	Sheth and Babu (2009)
Eucalyptus wood	0.29	6.3	2.29	88.11	Present study

4.2.5 Engine emission characteristics

The emissions from the exhaust of the engine shows to what extent the individual gases that make up the producer gas are utilized in the engine. It tells the quality of combustion reaction occurring within the engine. Figure 4.5 shows the quantity of gases that went into the engine and the quantity that came out through the engine exhaust.

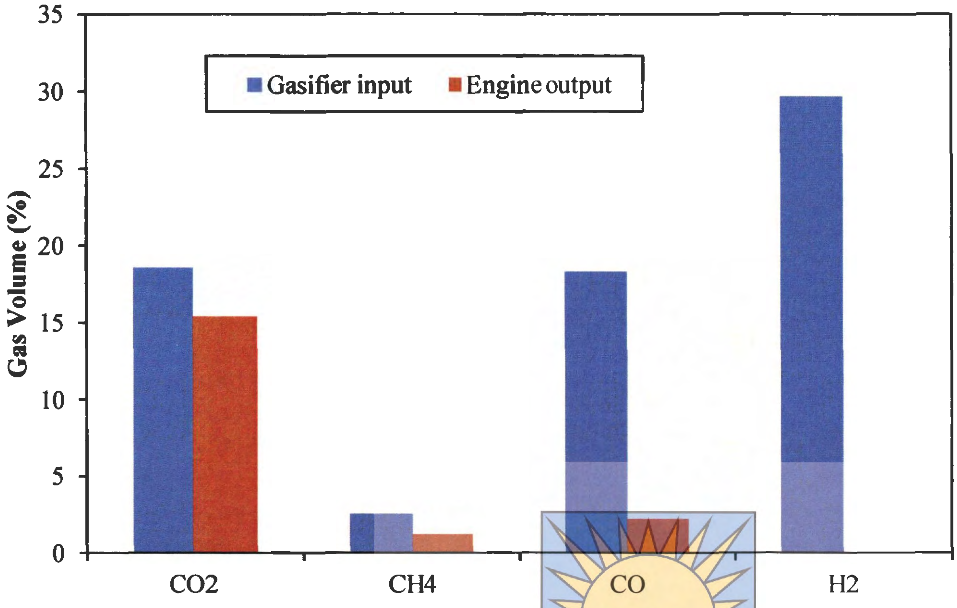

Figure 4.5: Comparison of gases emitted from the gas engine and gases fed into the engine

The hydrogen (H_2) that was supplied to the engine was totally consumed while for carbon monoxide (CO) 16.09% out of 18.31% was consumed leaving behind 2.22% which was released through the exhaust. For methane (CH_4) 1.19% was released which implies that 1.41% was consumed. The carbon dioxide (CO_2) released was 15.38%, which implies that 3.14% was consumed. The emission of CO is due to incomplete combustion taking place within the engine. It was expected that the quantity of CO_2 supplied to the engine would be equal to the one measured at the exhaust since CO_2 does not play a role in combustion. This therefore needs further research.

CHAPTER FIVE

SUMMARY CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY OF FINDINGS

Biomass gasification is an important technology and a good alternative to fossil fuel regarding its advantages. Its renewable nature which is at the top of the list is the most attractive bearing in mind that fossil fuel is non-renewable.

This study was conducted with an overall goal of evaluating the performance of the Johansson biomass gasifier system as this has not been ca[illegible] since the implementation of the project. The performance of the system was also evaluated to determine the technical viability of the project.

The physical and chemical properties of eucalyptus wood determined showed that the wood was suitable for gasification. The high volatile matter content obtained further proved the ease with which the wood was ignited. The moisture content of the wood obtained was well within the range required for gasification. No sulfur was found in the wood and that eliminated the risk of polluting the environment during gasification.

From the combustible gases produced during the operation of the biomass gasifier system hydrogen was found to be the highest in proportion. The heating value of the gas was then determined from the combustible component of the producer gas and was found to be 6.3

MJ/Nm^3 which is within the range obtainable for air gasification and higher than the average reported in other studies. It is also above the lower flammable limit and thus it could easily power a gas engine.

The mass balance of the system when operated on a full load revealed that 89.77% of the wood that was fed into the gasifier was converted to gas. It was also found that 1 kg of wood produced about 2.29 Nm^3 of gas while consuming about 1.69 kg of air. The energy balance further showed that out of a total of 6928.16 MJ of energy that entered the gasifier in the form of wood, 6104.7MJ was converted to gas. On average 1.075 kg of wood resulted in 1 kWh of electrical energy.

The thermal efficiency and electrical efficiency of the system then worked out to be 88.11% and 23.2% respectively while the overall (co-generative) efficiency gave 20.5%.

5.2 SUMMARY OF CONTRIBUTIONS

There are a number of biomass gasifier systems operating around the world. The Johansson biomass gasifier system installed at Melani village was the first gasifier installed to run about eight hours a day powering a community bakery. However there is still lack of gasifier performance information in South Africa and this was a major challenge that prevented potential investors from embracing the technology irrespective of its sound technical design.

The major contribution of this work is the provision of the much-needed technical performance data for the Johansson biomass gasifier. This could go a long way since potential investors will have independently collected data about the system performance, and this could stimulate investments in the technology and biomass gasification projects in the country. This research was also heavily motivated by the fact that potential investors were already looking for performance data, and since the beginning of the research a number of project developers have found the information useful so far.

5.3 CONCLUSIONS

Gasification is an efficient thermochemical conversion process that produces a gas mixture of hydrogen, carbon monoxide, carbon dioxide and methane. The heating value of the producer gas which was determined from the combustibles components of this gas has a strong dependency on gasification agent used. The mass and energy balance revealed that the system operates at high conversion efficiency. Conversion efficiency is a tool that determines the feasibility of using a biomass gasifier for energy conversion. The high values of efficiency obtained at the three stages of conversion confirmed that Johansson biomass gasifier system is a viable technology. The biomass gasifier under study was found to perform beyond its rating when operated on full load.

The proximate and ultimate analysis of the eucalyptus wood used for this study established that the wood was most suitable for gasification using the technology. It was also established that the eucalyptus wood has physical and chemical properties similar to those of most lignocellulosic biomass materials. These include mainly cellulose, hemicellulose and lignin. The chemical elements such as carbon, hydrogen, nitrogen and sulfur were also within the known ranges that are favourable for gasification.

An analysis of the syngas/producer gas before it entered the engine established that the gas has a slightly higher calorific value than the one reported in most studies. This was attributed to the high conversion efficiency associated with the design. The syngas composed mainly of hydrogen (29.6%), carbon dioxide (18.57%), carbon monoxide (18.4%), methane (2.6%) as well as nitrogen and other gases (30.83%) obtained by difference. The nitrogen content was higher because the system is air blown.

The mass and energy balance of the gasifier confirmed that about 27% of the input wood comes out as ash and fine carbon particles and the rest is converted to gas and heat. The gasifier managed to achieve cold gas efficiency of 88.11% and an electrical efficiency (gas to electricity) of 23.2%, and this was mainly due to the optimum fuel/air ratio of 0.29 that the system is designed to operate at. The system achieved a co-generative efficiency of 20.5%. The low electrical efficiency was due to the efficiency of the engine and generator used.

The engine emitted some of the gases that were supplied to it including a fraction of CH_4 and CO_2. It consumed all the hydrogen supplied with the gas stream. This was expected, except that the quantity of CO_2 emitted was slightly lower than the input CO_2. This is an aspect that needs further investigation since the engine was operating at very high efficiency.

5.4 RECOMMENDATIONS

Having evaluated the performance of the biomass gasifier system and determined its conversion efficiency at different stages. It is important to now investigate the impact of heat distribution on the conversion efficiency. The ability of the biomass downdraft gasifier system to uniformly distribute heat during gasification is crucial as this affects not only the conversion efficiency of the system but also the energy balance, economic and environmental performance of the gasifier system. It was established that the quantity of CO_2 supplied to the engine decreases after combustion. This needs further research. There is also a need for life cycle analysis of the chemical components of wood from gasification to the various products and by-products as well as the engine emission in detail.

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APPENDIX 1

Research output associated with this research

Nwokolo, N., Mamphweli, S., Meyer, E., Tangwe, S. (2013) Electrical Performance Evaluation of Johansson Biomass Gasifier System coupled to a 150KVA Generator, *Renewable Energy*, article under review Ref. No.: RENE-D-13-02155.

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