THERMO – CHEMICAL CHARACTERISTICS OF POTENTIAL GASIFIER FUELS IN SELECTED REGIONS OF THE LAKE VICTORIA BASIN

BY

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DECLARATION

Candidate

I declare that this thesis is my own work and it has not been submitted for any degree or examination in any other university and that all the sources used have been indicated and acknowledged by complete references.

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We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

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DEDICATION

To my parents, brothers and sisters for their Patience and Prayers

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ABBREVIATIONS AND ACRONYMS

BTU	British Thermal Units
EAC	East Africa Community
ANOVA	Analysis of Variance
LVB	LakeVictoria Basin
SNK	Student-Newman-Keuls
MPND	Ministry for Planning and National Development
DFID	Department For International Development
VM	Volatile Matter
MEMD	Ministry of Energy and Mineral Development
ER	Equivalence Ratio
NO_x	Nitrogen Oxides
TCD	Thermal Conductivity Detector
HHV	High Heating Values
LHV	Low Heating Values
FC	Fixed Carbon

ABSTRACT

Gasification technology has failed to take off in a number of developing countries including East Africa despitebeing the most efficient way of converting biomass into energy. All countries in the Lake Victoria Basin (LVB) depend mostly on hydroelectric power for provision of modern energy.While hydropower is sensitive to climate change, gasification technology has a high potential for reducing biomass energy consumption while increasing access to electricity and clean cooking facilities thus improving income and livelihoods. The key aspect for failure is the insufficient adaption of gasification equipment to fuels characteristics, fuel specification and inadequate material choice of system components. The study investigated thermo-chemical characterization of six biomass fuels, namely *Pinus caribaea*, *Calitris robusta*, *Cupressus lustitanica*, *Eucalyptus grandis*, *Pinus patula* and sugarcane bagasse in selected regions of Lake Victoria Basin ((LVB). Ultimate analysis was determined using Flash 2000 elemental analyser. Moisture content, ash content and volatile matter (proximate analysis) were determined in an oven and muffle furnace while heating values were determined using Gallenkamp Auto bomb calorimeter. The mean percentage levels obtained in this study indicates that all the six biomass fuel had mean range for N between 0.07 ± 0.2 and0.25±0.07, C, 40.45 ± 0.61 and 48.88 ± 0.29, H, 4.32 ± 0.13 and 5.59 ± 0.18 and O, 43.41 ± 1.58 and 51.1 ± 0.64. For Proximate analysis, moisture content ranged between 25.74 ± 1.54 and 56.69 ± 0.52, ash content,0.38 ± 0.02 and 2.94 ± 0.14, volatile matter, 74.68 ± 0.49 and 82.71 ± 0.19 and fixed carbon, 14.35 ± 0.33 and 24.74 ± 0.27. The Heating values ranged between 16.95 ± 0.10 and 19.48 ± 0.42 MJ/kg. *Cupressus lustitanica* from Kakamega gave 49.09 ± 0.16 % C compared to that of Kodera which gave 47.96±0.75 %.*Pinus caribaea*from Wakiso gave 0.27±0.08 % N compared to Kodera which gave 0.16 ± 0.04 %.Energy content of *Pinus patula* from Kodera was19.48 ± 0.30 MJ/Kg compared to that of Kibiri which was 17.87 ± 0.05 MJ/Kg. The theoretical syngas composition as calculated from thermodynamic equilibrium model gave the percentage range of CO_2 as between 9.79 ± 0.11 and 13.02 ± 0.26, H_2, 15.04 ± 0.54 and 16.52 ± 0.43 and CO, 24.39 ± 1.43 and 26.66 ± 1.78. The results suggest that all the six biomass fuels are potential biomass gasification materials, but considerations should be made on the gasifier type to be used.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Modern energy, such as electricity, is crucial in order to achieve the Millennium Development Goals (MDG’s) of poverty reduction, improved education and environmental sustainability (Modi *et al*.,2006). Currently, about one third of the world’s populations or two billion people, have only intermittent access to electricity and clean cooking facilities.

Biomass covers a broad range of materials that can be used as fuel or raw materials. They are natural mterials and their derivatives (Highman and Van der Burgt, 2008). Sources of biomass include various natural and derived materials, such as woody(example from forest thinning and harvesting, timber production and carpentry residues),herbaceous species, agricultural and industrial residues, waste paper, municipal solid waste, grass, waste from food processing, animal wastes, aquatic plants and industrial and energy crops grown for biomass (Klass, 1998). Although biomass is not a major industrial fuel, it supplies between 15 and20 percent of the total fuel use in the world and 38 percent of biomass energy in the developing countries (Woods and Hall, 1994; Goldemberg, 2000; McKendry, 2002; Karekezi *et al*., 2004;Highman and Van der Burgt, 2008).

Biomass is used mostly in non-industrialized economies for domestic heating and cooking. In industrialized countries, the use of biomass as a fuel is largely restricted to the use of by-products from forestry, paper and sugar industries. Nonetheless, its use in industrialized countries is being encouraged as part of strategy for CO_2 reduction (Highman and Van der Burgt, 2008).In principle, biomass is a less damaging and environmentally benign fuel as the carbon dioxide released from the combustion process is captured during the plant growth.

In East Africa, 81 percent of the populations live without access to reliable and affordable access to clean cooking facilities (EAC, 2009). In Kenya, biomass (firewood and charcoal) constitutes about 70 percent of the national energy supply, 90 percent of which is consumed by households. The other 10 percent of biomass energy is consumed by communal institutions and kiosks (MPND, 2006). The Uganda National policy and the renewable Energy policy, show that the energy sector in Uganda is dominated by traditional biomass based fuels, which contribute up to more than 93 percent of the total energy consumption in the country (MEMD, 2007). About 84 percent of the households are located in rural areas but less than 1 percent of them have access to modern energy services.

Electricity and clean cooking facilities in the East Africa region are grossly inadequateand traditional biomass currently meets most of the regions households cooking and heating needs (EAC, 2009).Women and children inhale indoor fumes while cooking and spend considerable amounts of their productive time collecting dwindling and distant supplies of wood(Reddy *et al*.,1997; Bailis *et al*., 2005; EAC, 2009). The lack of access to reliable and affordable clean cooking facilities results in a lower quality of life, limited opportunities for economic development and environmental degradation. Surprisingly, the absence of basic modern energy services is not necessarily a result of financial poverty. Many of the poor already pay more per unit of energy than the middle and upper class due to inefficient technology and corruption (DFID, 2002).

Various technologies with efficiency in energy production are available and can be operated with minimal training. Gasification technology, for example, can run household and small scale industries which add value to agricultural products such as grain mills, drying or cooling chambers, run machinery for local manufacturing, improve local health services by refrigeration of vaccines, enable access to communication and information technologies and increase daily productive hours by providing light in houses, commercial and public buildings (Keyun, 1993; Ravindranath *et al*.,2004; Nouni *et al*., 2007*)*.

Burning wood in an open fire is very inefficient and much of the heat is lost which is very wasteful. Much effort over time has been spent trying to improve conventional wood stoves. Micro gasifiers or 'micro-gasification' is a technology that works and is quite different as the "gasifiers separate the generation of combustible gases from their subsequent combustion to create cooking heat. A biomass gasifier is the broad term for a device that turns solid biomass into gas that can subsequently be burnt in a controlled manner. Unlike in the open fire, the gas-generation is controllably separate in space and time from the gas-combustion (Roth 2011).

Gasification technology, has failed to take off in a number of developing countries including those in East Africa. According to Stassen (1992), analysis reveals that this is due to a number of underlying reasons such as technical, financial and organisational aspects.The key aspect for failure is the insufficient adaptation of gasification equipment to fuel characteristics, fuel specifications and inadequate material choice of system components.The biomass feedstock is one of the most important defining inputs in determining the efficiency of gasification reactions. This is because the reactions are highly dependent on chemical feedstock composition. The composition of the producer gas is strongly dependent on the chemical composition of the feedstock (Knoef *et al*., 2005).

The different biomass characteristics result in the necessity to pretreat/process different types of biomass feedstock before use as gasifier fuel. Feedstock preparation is required for almost all types of biomass materials because of large variations in their physical, chemical and/or morphological characteristics. The degree to which any specific treatment is desirable will depend on the details of the gasifier plant. The sequence of pretreatment technologies depends on the type and characteristics of the biomass material and the requirements of the gasifier fuel (Knoef *et al*., 2005). In downdraft gasifier (figure 1.0)for example, the moisture content of biomass feedstock must be reduced to about 20percent or less for proper functioning of the downdraft gasifier (Knoef *et al*., 2005).

Figure 1.1Downdraft gasifier (Jorapur and Rajvanshi, 1997)

Stevens e*t al*.(1985) stated that "the efficiency of biomass processes is extremely dependent upon recognizing and exploiting the chemical and physical properties of the biomass". Burtner *et al*.(1988)showed a detailed chemical and physical characterization of the feedstock usefulness in identifying plant constituents that correlate with the products. This helps to tailor the nature of the biomass to suit specific requirements such as design of gasifiers (Davis *et al*.,1984). Ragland *et al*.(1991) indicated the importance of adequate knowledge of wood properties for the analysis and modeling of gasifiers, combustion stoves, furnaces and industrial processes. Miller(1982) observed that for specialty or developing uses like feedstocks for chemical extraction, co-firing in fluidized beds, liquefaction and gasification, variation in the fuelwood characteristics may influence selection of suitable feedstocks and may even restrict possible uses.

One of the key aspects to alleviate poverty among the rural populace in the Lake Victoria Basin(LVB) will be to ensure that there is adequate, reliable and sustainable supply of energy services to the rural communities. Fortunately, the basin is located on the equator and as result receives an abundant insolence averaging 4.5kWh/m^2/day (MEMD, 2005).This provides the necessary conducive environment for vast growth of biomass. The range of biomass available includes trees, shrubs, agro and forest wastes. Some of the abundant shrubs for example *Lantana camara* are currently regarded as weeds but with appropriate conversion technologies they could be turned into a potential resource for fuel. Some trees like *Senna spectabilis* have been found to be invasive in Uganda (Bagabo,2009*)*, but could also be fuel resources. Peat is another resource that has a large potential for fuel production in the LVB. The total volume of peat is estimated to be 6,000 million cubic meters. The dry bulk density averages at 100kg/m^{3}witha net calorific value 17 MJ/kg. The estimated theoretical peat volume represent about 250 million oil equivalent tons (MEMD, 2007).

1.2 Problem statement

There is a wide variation in biomass characteristics in the Lake Victoria basin.The biomass characteristics accounts in part for the large number of gasifier design available today. The gasifier used during World War II used specially prepared hardwood blocks. However, such blocks could represent only a tiny fraction of the biomass materials available for gasification. Some gasifiers currently are undergoing design evolutions that will enable them to use a wider range of fuels; nevertheless, fuel properties are important in determining satisfactory operating conditions of the gasifiers. Therefore, these gasifiers will be able to use only a limited range of biomass with controlled specification and anyone installing a gasifier should have knowledge on biomass characteristics before deciding upon a purchase.

The characteristics and quality of a fuel vary widely, depending on the type of biomass sample and the pre-treatment applied. The parameters affecting the properties of fuels include the chemical composition (the content of such elements as carbon, hydrogen, nitrogen and sulfur), moisture content, the amount of volatile matters, the amount of solid carbon, ash content, the amount of impurities and dust. There is a need to determine biomass characteristics for the proper gasifier design among the communities in the East Africa Region.

1.3 Justification

Access to electricity and clean fuels for both urban and rural populations is a major policy priority for all governments in the East Africa Community. Rural electrification is mostly depending on main grid extensions which are also mainly depend on hydro resources.However, between 2004 and 2005, prolonged droughts, which were a result of climate change, significantly reduced water levels both in the rivers and the Lake Victoria itself. This affected power generation forcing all states to increase thermal electricity generation (based on fossil fuels), with its accompanying negative environment effects and high cost per unit. Climate change is likely to affect infrastructure for energy production, transmission and distribution.Utilities may experience a higher rate of failure, with attendant costs. This phenomenon, will greatly affect energy security and economic development activities in the LVB. Planning and implementation of sustainable development programmes in the LVBneed to integrate energy adaptation measures to climate change.Biomass gasification offers one of the most viable energy adaptation alternatives.

1.4 NullHypotheses

(i)Biomass fuel types do not differ in their chemical characteristics in the LVB

(ii) Biomass fuel types do not differ in thermo characteristics in the LVB

(iii) Biomass fuel types do not differ in syngas composition in the LVB

1.5 Objectives

1.5.1 General objective

To determine the thermo-chemical characteristics of gasifier fuels in the LVB

1.5.2 Specific objectives

(i)To determine the percentage content of Nitrogen, Carbon, Hydrogen and Oxygen in selected biomass fuels in the LVB.

(ii) To determine the percentage content of ash, moisture, volatile and fixed carbon in selected biomass fuels in the LVB.

(iii)To determine the calorific value of biomass fuels in selected regions in the LVB.

(iv) To calculate biomass synthesis gas composition using thermodynamic equilibrium modeling.

1.6 Significance of the study

Due to the depleting fossil fuel supplies and increasing energy consumption resulting from increasing populations and economic development, it is critically important to explore alternative energy sources for ensuring a sustainable future. Biomass is clean and renewable alternative and can be excellently substituted for conventional fuels. Renewable fuels are cleaner fuels which reduce environmental pollution, greenhouse gas emissions and global climate change. Among all biomass conversion technologies biomass gasification is most efficient in converting biomass into energy.

LVB is endowed with abundant biomass feedstocks for gasification. For gasification applications, an ideal biomass feedstock is expected to be renewable, readily available, result in sufficient combustible gases, be environmentally acceptable and have sufficient heating values. The studies determined the thermo-chemical characteristics of biomass for meeting gasification processes and help the community to adopt biomass gasification.

The result contributes towards increased energy production and generating knowledge on adaptation of small-to-medium scale biomass gasification technology for industrial, institutional and commercial purpose. These would stimulate growth in farming, forestry and rural industry leading to overall rural development. Biomass energy could also provide a productive avenue for using agricultural and forestry wastes, besides plantations. The results of the study will be availed to the relevant ministries in EAC to educate the public about the importance of adopting biomass gasification.

CHAPTER TWO

LITERATURE REVIEW

2.1 Lake Victoria Basin

Geographically,the Lake Victoria Basin (figure 2.1) includes Kenya, Tanzania, Uganda, Burundi and Rwanda. The latter two countries are part of the LVB catchment areas as a number of tributaries originate in these countries. The LVB occupies an area of about 240,000 square kilometers of which about 69,000 squarekilometers are the lake itself.The largest part of the LVB lies in Tanzania at 44percent, followed by Kenya at 22percent, Uganda at 16percent, Rwanda at 11percent and Burundi at 7percent (FAO, 2002; Lillehammer *et al*, 2005). Water from the Lake Victoria is a trans-boundary resource shared between Kenya, Tanzania and Uganda. The inflows to the lake from major and small tributaries contribute about 13percent of the water entering the lake annually, while the remaining 87percent comes from rainfall (Howell*et al.*, 1988).

Most parts of the LVB are characterized as semi-arid with the exception of some areas close to the lake which have a relatively high rainfall of between 1200 - 1500 millimeters per annum (Kull, 2006). The LVB is estimated to host a human population of about 30 million. The main economic activities include agriculture, fishing, hydroelectric power generation and trade. Agriculture, however, is the dominant economics activity in the LVB, supporting over 80 percent of gross domestics’ product (GDP).

Figure 2.1:Map showing LVB between the 5 countries (World Bank, 2006)

2.2 Biomass feedstock characteristics

Biomass fuels available for gasification include charcoal, wood and wood waste (branches, twigs, roots, bark, woodshavings and sawdust) as well as a multitude of agricultural residues (maize cobs, coconut shells, coconut husks, cereal straws, rice husks, etc.) and peat (Li, 2002).The fuels have different demands on the method of gasification and consequently require different reactor designs and gasification technologies. It is for this reason that during a century of gasification experience, a large number of different gasifiers have been developed and marketed. All types of gasifiers are geared towards handling the specific properties of a typical fuel or range of fuels (Quaak *et al*., 1999).Thus it follows that the "universal" gasifier, able to handle all or most fuels or fuel types, does not exist, and in all probability will not exist in the foreseeable future (FAO, 1986).

Gasifiers designs include updraft, downdraft, crossdraft, fluidized bed as well as other biomass gasification systems of less importance. All systems show relative advantages and disadvantages with respect to fuel type, application and simplicity of operation. It is for this reason each gasifier will have its own technical and/or economic advantages in a particular set of circumstances (Quaak *et al.*, 1999).

Each type of gasifier operate satisfactorily with respect to stability, gas quality, efficiency and pressure losses only within certain ranges of the fuel properties. The most important properties include: moisture content, energy content, volatile content, ash content, amount of fixed carbon and elemental composition of the fuel (Quaak *et al.*, 1999).Before choosing a gasifier for any individual fuel, it is important to ensure that the fuel meets the requirements of the gasifier or that it can be treated to meet these requirements. Practical tests are needed if the fuel has not previously been successfully gasified (FAO, 1986).

2.2.1 Moisture content

Biomass contains moisture intrinsically by nature or extrinsically by absorbing from the surrounding atmosphere (Mackendry, 2002; Roy *et al.*, 2009). Moisture content, during gasification, increases CO_2 concentration by the water-shift reaction which consumes CO and liberates H_2 (Zainal *et al.*, 2001; Melgar *et al.*, 2007; Roy,*et al.*, 2009). While the equilibrium constant for water-shift reaction varies little over a wide range of temperatures, the direction tends to reverse at higher temperature. More heat is required for moisture evaporation compared to the amount gained due to the exothermic behavior of the water-shift reaction.

Thermal energy, therefore inside the gasifier reduces when gasifying biomass with higher moisture content is used (Lee, 1996). These decreases in temperature further exacerbate the scenario. More $CO_2$is formed since the water-shift reaction is improved at lower temperature. The overall effect is the reduction in calorific value of resultant synthesis gas(Shin *et al*.,2000; Zainal *et al*., 2001; Altekini, *et al*., 2003;Melger *et al*., 2007; Sharma, 2008; Roy *et al*., 2009).

The negative effect of moisture content on the calorific value of synthesis gas is lower at lower equivalence ratio (ER) (Zainal *et al*., 2001; Melger *et al*., 2007). The ER is the ratio of actual air fuel ratio to the stoichiometric air fuel ratio. It provides the basis forevaluating the amount of air supplied for the gasification with respect to the amount of air required for the complete combustion of the feedstock (Zainal *et al*., 2001). Roy *et al*.(2009) observed that in a downdraft gasifier, when the moisture content is increased from 0 to 40percent, heating value of synthesis gas decreases by 8.72percent at ER of 0.45 while the decrease was 4.7percent when the ER used was 0.29. This result was reported from their equilibrium model and thus is applicable to any gasification process. Table 2.1 summarizes the effect of moisture content in three common gasifier types (Reeds *et al*., 1988; Dogru *et al*.,2002a).

Table 2.1 Effect of Moisture Content in Three Common Gasifier Types

Parameter	**Gasifier type**	**CO**	**CO_2**	**H_2**	**CH_4**	**Maximum limit(% wet basis)**
Moisture content (M.C)	Updraft	-[a]	+[b]	+	~[c]	<50
	Downdraft	-	+	+	~	<20
	Fluidized	-	+	+	~	<10
[a] decreases with increase in M.C, [b] increase with increase in M.C, [c] no significant change						

Table 2.1 effect of moisture content (Dogru *et al*., 2002a)

Table 2.1 shows that when moisture content is increased carbon dioxide increases, decrease the carbon monoxide and increases hydrogen content. A limiting condition called auto-thermal limit is outlined at 65percent moisture content (Reeds *et al.*, 1988). Beyond the limit, self-sustaining gasification is not possible.This is due to enthalpy deficiency for vaporization (Jenkins*et al.*, 1998). In fact, supplemental fuel is required for most of the combustor when the moisture content is greater than 50percent on a wet basis (Reeds *et al.*, 1988; Jenkins*et al.*, 1998;Dogru *et al.*, 2002b).

When air is used as the gasification agent, the amount of methane produced is little and almost constant with change in moisture content (Zainal *et al.*, 2001; Gautam *et al.*, 2010). Thus the temperature decrease inside the gasifier due to moisture also results inlower mass conversion efficiency and increases tar content (Jayah *et al.*, 2003;Melgar *et al.*, 2007;Ptasinski *et al.*, 2007; Ratnadhariya *et al.*, 2009). Sheth and Babu (2009) reported the decrease in biomass consumption rate with increase in moisture content. This is due to thehigher amount of heat needed for drying the wood chips before they canbe pyrolyzed. However, some moisture content is desirable since it enhances steamreforming and helps to crack tar. At higher temperature, it enhances other reactions such aschar gasification (Narvaez *et al.*, 1996; Li *et al.*,2004). Steam injection is widely used in industrial applications to adjustsynthesis gas composition in the gasification process but often, in the presence of higher temperatureprovided by some external source (Li *et al.*, 2001).

2.2.2 Energy content

The heat value of a fuel is a measure of the amount of energy that is released through combustion of a unit mass of sample.The maximum amount of energy that can be potentially recovered when fuel is completely combusted under controlled (adiabatic) conditions is known as the high heat value (HHV) or calorimetric or calorific heat value (CHV) (McKendry, 2002). This energy is independent of the moisture content of biomass and includes the latent heat of vaporization recaptured by the condensation of vapour within the system (McKendry, 2002; Basu, 2010). In practice, however, the energy used during vaporization of water (both the inherent water of constitution from hydroxyls and acquired moisture) is lost as the latent heat of vaporization. This reduced energy can be expressed either as a function of the inherent moisture, that is Low heat value (LHV) (MJ/kg), also known as the Effective heat value (EHV) (Hakkila and Parikka, 2002) or as a function of the acquired moisture, that is Net heat value (NHV) (White *et al*.,1983).

Heating value or calorific value or heat of combustion is the energy content of a biomass fuel (Sheng and Azevedo,2004; Demirbas, 2007). Anuradda *et al*. (1996) showed that the heating value was necessary to determine the suitability of biomass for pyrolysis, carbonization, liquefaction and gasification. Heating value is a function of the chemical composition, in particular with the carbon content (Susott *et al*., 1975; Doath, 1977). Variations in the heating values among different species and different plants components shows differences in the chemical composition which is used to demonstrate the quality of the fuel.

The heating values of different biomass materials (such as various tree species and crop residues) differ significantly. Heating value reflects the collective heating values of the wood components (Tilman, 1978). Different components of Douglas fir for example, have been found to have different heating values. The hollocellulose (cellulose and hemicelluloses) have 17.5 MJ/kg, lignins have 26.7 MJ/kg, and extractives have 34.4-39.5 MJ/kg (Corder, 1975; Tilman, 1978; Kubler, 1982). Wang and Huffman (1982) showed the influence of different extractive contents levels on the heating values of wood (in *Melaleuca quinquenervia*) material as ranging from negligible in the sapwood where the extractives content is very low, to 37percent of the materials energy. Thus, there is a relationship between the lignin and extractives contents of wood fuel, and its energy value (White, 1983). Measurements using differential scanning calorimetry have shown that water soluble extractive compounds have the greatest per unit energy content of the wood components (Krigstin *et al.*, 1993). Removal of these materials leaves a low energy residue with about 16.8 MJ/kg and containing a proportionately higher content of oxygen.

Corder(1975) observed that the heating values for different tree species on a moisture free and resin-free basis is the same, being equivalent to about 19.5 MJ/kg. Resin (one of the extractives) has a higher heating value than wood itself (with 39.5 MJ/kg). Thus, woods that contain a lot of resins such as pines, spruce, cedars, larch and Douglas fir (softwoods) have higher heating values ranging from 20.00-22.6 MJ/kg. The near resin-free woods such as true firs and most hardwoods like beech,elms, red beech,red maplebeech, red maple, hickory, oak and sycamore have values ranging from 18.5-19.0 MJ/kg. However, the heating values quoted for most wood species by other workers (Wanfg and Huffmam, 1982; Rossi, 1984; Najewicz and Furham, 1993) particularly for hardwoods are much lower than the minimum value for corders resin-free wood. The highest quoted values are for Douglas fir bark and wood respectively at 21.93 and 20.37MJ/kg oven dry weights. The lowest values quoted are for black oak (Quercus species) bark and wood having 17.09 and 18.65MJ/kg, respectively (Rossi, 1984). The value quoted for hybrid poplars is 19 MJ/kg (Paisley and Litt, 1993), for willows is 19.2-19.6 MJ/kg (Krigstin, 1985). Sastry and Anderson (1980) found significant difference in the heating values ranging from 18.2 MJ/kg to 20.7 MJ/kg in 10 hybrid popular clones. Wang and Huffman (1982) determined the calorific values of extracted and un-extracted of tree components from two different species. Though extracted and un–extracted values were different, extracted materials did not have similar calorific values as suggested by different tree components have different heating values. Howlett and Gamache (1977) reported values of 17.7-21.0 MJ/kg for foliage materials, being higher in the foliage of softwoods. Although Haris (1985) found that red maple (*Acer rubrum*) and post oak (*Quercus stellata*)woods had higher heating values than bark of the same tree, most reports suggest that bark from the same tree and position has a higher heating value than the wood (Howlett and Gamache, 1977). Molner and Nemanth (1983) found that the heat of combustion for bark of Robinia species was 7.2percent higher than that of stem wood. Tieteme *et al*. (1991) foundhigher calorific values for bark than wood in arid species using the Wagner techniques.

2.2.3 Ash content

Ash is the mineral contents of fuel which remains in oxidized form after combustion of fuel. In practice, ashes also contain some unburned fuel. Ash content and ash composition have an impact on smooth running of gasifier. Melting and agglormeration of ashes in reactor causes slagging and clinker formation.High ash content causes slagging and consequently ash agglomeration due to fusion, the rate of which is dependent upon the ash content in biomass and ash composition (Jenkins *etal*., 1998; Ryu *et al*., 2006; Livingston, 2007). If no measures are taken, slagging or clinker formation leads to excessive tar formation or complete blocking of reactor. In general, no slagging occurs with fuel having ashcontent below 5 percent.

Although formation of clinkers can cause problems for the gasifier operation with biomass having ash-content above 5percent, successful gasification with ash-content up to 25percent has been reported (Mckendry, 2002). High ash content biomass should be gasified at the temperature below the oxidation or reducing temperature of the minerals constituents in the ash. This is often not possible if the constituents have relatively low ash-fusion temperature

(Milne and Evans, 1998; Gerun *et al*., 2008). Common ash oxides in biomass are silicon, potassium, calcium, aluminum, magnesium, iron, sodium and chlorine. These minerals present in biomass can exist as salts and vaporize during the gasification process contaminating the synthesis gas. It is also highly possible for these minerals to react with silicon in presence of oxygen to create low-temperature melting silicates which can create a severe deposition problem. Potassium and calcium silicates have melting temperatures even below 700°C (Jenkins *et al*., 1998). One way to tackle the problem is to resort to some kind of removal process like leaching the alkali metal which has been reported to reduce these minerals by more than 80percent. Removal of these alkali metals will increase the ash fusion temperature thus facilitating gasification (Jenkins *et al*., 1998).

The ash in biomass requires careful control over the operating temperature. Neither should it be high enough to fuse minerals in the ash forming a barrier to further gasification by formation of clinkers, nor too low leading to unburnt carbon resulting in lower carbon conversion efficiency. Biomass Technlogy Group (BTG) (1995) reported that downdraft gasifier can handle biomass fuel with 0.5 % ash (maximum 6%), updraft gasifier with 1.4 % ash (maximum 25%) and fluidized bed gasifier with less than 25 % ash on dry basis.

2.2.4 Volatile matter and fixed carbon

Volatile matter (VM) content is a measure of the carbohydrate content of the fuel which is convertible to hydrocarbons (Will, 1979). Fixed carbon (FC) is the mass remaining after release of volatile and excluding the ash (Mckendry, 2002).Fixed carbon (FC) is calculated by difference from VM and ash amount Thus FC is calculated using equation 2.0

$$\% FC = 100 - (\% VM + \% Ash) \quad \text{.....} 2.0$$

where FC is fixed carbon and VM is volatile matter

VM indicates the hydrogen/carbon ratio of solid fuels and the percentage of fuel burnt in a gaseous state as opposed to the fixed carbon content which shows the fuel burnt out in the solid state. Biomass feedstock contains a very high proportion of volatile organic materialof about 70 to 90percent for wood (Klass, 1998; Alakangas, 2000).

The amount of volatiles in the feedstock determines the necessity of special measures. It is either in design of the gasifier or in the layout of the gas cleanup traps in order to remove tars from the product gas in engine applications. In practice, the only biomass fuel that does not need this special attention is good-quality charcoal. VM in charcoal however is often underestimated and in practice may range from 3 to 30 percent or more. As a general rule, if the fuel contains more than 10 percent VM, it should be used in downdraught gas producers, but even in this case the method of charcoal production should be taken into account. Charcoal produced in large scale retorts is fairly consistent in VM compared to one produced from small scale open pits or portable metal kilos that are common in most developing countries (FAO, 1986).

Volatiles produce tars during pyrolysis while fixed carbon produces char. In a gasifier, the tars can either be combusted with oxygen or thermally cracked. Char is needed for reduction. Gasifiers will generally operate better with more fixed carbon in the fuel. Wood have averages of 20 % fixed carbon and 80% volatiles (Mckendry, 2002).The fixed carbon also affects the heating value of a fuel in such a way that the higher the fixed carbon, the higher the heating value of a fuel. In general, an increase in ash content corresponds to a decrease in the fixed carbon content (UNESCO, 1988).

2.2.5 Ultimate analysis

Ultimate analysis is basically an elemental analysis of biomass. It involves measurement of carbon, hydrogen, nitrogen, sulphur and oxygen content. Carbon is the most important element in the fuels since it reacts exothermically with oxygen to produce heat required to sustain further thermochemical processes. Ultimate analysis is necessary for calculating stoichiometric air requirements for flue gas analysis in gasification. It indicates the theoretical energy content. A more detailed elemental analysis is required in evaluation and control of operations with certain biomass fuel materials(BTG, 1987). Ultimate analysis is usually reported on a dry and ash-free basis, to avoid the effects of contamination of sample with soil and the variability of the moisture content. Table 2.2 lists the major elemental components in typical biomass (BTG, 1987).

Table 2.2: Elemental Composition of Typical Biomass

Element	**Weight percent (dry and ash-free basis)**
Carbon	42-51
Hydrogen	5.5-6.7
Oxygen	41-50
Nitrogen	0.12-0.60
Sulfur	0-0.2

The heat content is related to the oxidation state of the natural fuels in which carbon content generally dominate and overshadow small variations of hydrogen content. On the basis of literature values for different species of wood, Tilman (1978) found a linear relationship between Higher Heating Values(HHV) and carbon content.Demirbas(1997) developed a formula for estimating the HHVs of fuels from different lignocellulosic materials, vegetable oils, and diesel fuels using their ultimate analysis data. For biomass fuels, HHV was calculated using the modified Dulong's formula, as a function of the carbon, hydrogen, oxygen and nitrogen contents.

2.3 High Heat Values Derived from Theoretical Equations

The heating value of biomass is an indication of the energy chemically bound in it, which is converted into heat energy through a combustion process. The heating value is the most important property of a fuel which determines its energy value. The design and control of a biomass combustor and gasification depend strongly on the heating value of a biomass fuel (Erol*et al*.,2010).

The heating value of a biomass fuel is determined experimentally by employing an adiabatic bomb calorimeter, which measures the enthalpy change between reactants and products. However, the measurement is a complex and time-consuming process that requires the set-up, measurement and calculation procedures. In contrast, the conventional analysis, that is proximate and ultimate analyses, is a basic fuel characterization and can be carried out in an easier, quicker and inexpensive way by using common or modern laboratory equipment. Therefore, many attempts have been made to estimate the HHV based on correlating the heating value of biomass with the data of proximate analysis (Tilman, 1978; Jimenez and Gonzales, 1991; Demirbas, 1997; Cordedo*et al*.,2001) and of ultimate analysis (Institute of Gas Technology, 1978; Graboski and Bain, 1981; Annamalai *et al*.,1987; Jenkins and Ebeling, 1985; Channiwala and Parikh, 2002; Sheng and Azvedo, 2005). On the other hand, calculation may also be used as a general check of the accuracy of the observed data (Erol*et al*.,2010). The table 2.3 lists some equation for estimation of HHV.

Table 2.3 Estimating HHV using theoretical equations

Reference	empirical equation
Based on proximate analysis	
Sheng and Azvedo (2005)	$HHV= 19.914 - 0.2324 \times Ash$
Demirbas (1997)	$HHV= 0.196 \times FC+14.119$
Jimenez and Gonzales (1991)	$HHV= 10.81408+0.3133 \times (VM+FC)$
Demrbas (1997)	$HHV= 0.312 \times FC + 0.1534 \times VM$
Cordedo *et al*.(2001)	$HHV= 0.3543 \times FC+0.1708 \times VM$
Sheng and Azvedo (2005)	$HHV= -3.0368 + 0.2218 \times VM + 0.2601 \times FC$
Based on ultimate analysis	
Tilman (1978)	$HHV= 0.4373 \times C-1.6701$
Sheng and Azvedo (2005)	$HHV= 0.3259 \times C+3.4597$
Jenkins and Ebeling (1985)	$HHV= -0.763+ 0.301 \times C+ 0.525 \times H+0.064 \times O$
Sheng and Azvedo (2005)	$HHV= -1.3675+ 0.3137 \times C+ 0.7009 \times H+0.0318 \times O$
Demirbas (1997)	$HHV= 0.335 \times C+ 1.423 \times H- 0.154 \times O-0.145 \times N$
Annamalai *et al*.(1987)	$HHV= 0.3516 \times C+1.16225 \times H -0.1109 \times O+ 0.0628 \times N+0.10465 \times S$
IGT(1978)	$HHV= 0.341 \times C+ 1.322 \times H- 0.12 \times O - 0.12 \times N+ 0.0686 \times S -0.0153 \times Ash$
Graboski and Bain (1981)	$HHV= 0.328 \times C+1.4306 \times H-0.0237 \times N+0.0929 \times S-(1- Ash/100) \times (40.11H/C)+0.3466$
Channiwala and Parikh (2002)	$HHV= 0.3491 \times C+1.1783 \times H+0.1005 \times S - 0.1034 \times O- 0.0151 \times N- 0.0211 \times Ash$

Biomass composition, VM, FC, Ash, C, H, O, N, S are weight percent on dry biomass basis.

2.4Biomass Gasification

Biomass gasification was intensively used to operate farm and transportation systems during the World War II (Breag and Chittenden, 1979). It can be described as a process that involves incomplete combustion of biomass to produce combustible gases, which include carbon monoxide, hydrogen, methane and tar (Richey, 1984; Stassen, 1995; Adnan,*et al*., 2001; Dasappa,*et al*., 2004). This blend is called producer gas or synthesis gas. It can be utilized to run internal combustion engines, to substitute furnace oil in direct heat applications or to produce methanol for industrial or heat engines (Rajvanshi, 1986; Kartha and Larson, 2000; Stevens, 2001; McKendry, 2002).

Historically, gasification was conducted at low temperatures where biomass was partially combusted or oxidized. Partial combustion or biomass oxidation yields a low energy content gas compared to gasification. The quality of the gas derived from partial combustion was usually poor, as it contained impurities and too much fuel was required to power any system. Over the decades, gasification has been improved and is now a more efficient thermo chemical technology of converting biomass into energy (Johansson and Goldemberg, 2002). If conducted in accordance to system specifications, the technology is capable of performing at more than70 percent efficiency (Reed and Das, 1998; Demirbas, 2004). The product of gasification is either a low- or medium – British thermal unit (Btu) gas depending on the process employed. This producer gas retains about 70-80percent of the original biomass energy (Reed and Das, 1998).

Walker (2006) reported that the process of gasification occurs by heating biomass to high temperature (1200 – 1400^{o}C) in an oxygen deprived environment, therefore limiting combustion. The process takes place in four stages namely drying, devolatilization, gasification and finally combustion. The first phase of heating and drying is unproductive in terms of energy output, as energy is used to evaporate remaining moisture from the biomass. In the pyrolysis phase volatile components of the biomass are removed. The temperature range in this stage is 450 – 600ºC. Pyrolysis vapour is comprised of water, carbon monoxide, hydrogen, methane, volatile tars and carbon dioxide. The remaining biomass is a carbonized solid fuel charcoal, with 10 - 25 percent of the original fuel mass. The final stage at temperatures between 700ºC -1200ºC involves the conversion of char into producer gas that constitutes about 16 percent CO, 20 percent H_2, 50 percent N_2,12 percent CO_2, 2 percent CH_4 and products such as ash and powder slag (Heesch *et al*., 1999 ;Torres, 2007).

2.5 Gasification reactions

Biomass gasification is similar to that of coal in the sense that thermal decomposition of both solids occurs to yield a mixture of essentially the same gases (Klass, 1998). However, biomass gasification occurs under much less severe operating conditions than for coal feedstock because its main constituents, the high-oxygen cellulosics and hemicellulosics, have higher reactivity than the oxygen-deficient, carbonaceous materials in coal (Klass, 1998). The thermo-chemical processes involved in gasification are drying, pyrolysis, oxidation and reduction.

Drying involves evaporation of the moisture contained in the biomass. At temperatures above 100℃, water in the biomass fuel is converted to steam. Part of this vapor may be reduced to hydrogen during gasification and the rest ends up as moisture in the produced syngas.During pyrolysis, biomass fuels begin to pyrolyze at temperatures above 200ºC (Wei, 2005). This is the thermal decomposition of the fuel into volatile gases and char. The proportion of these components is influenced by the chemical compositions of bio-fuels being fed and the operating conditions of the gasifier (Wei, 2005). The main process of thermal decomposition of biomass can be represented in equation 2.1

$C_6H_{10}O_5 + \text{Heat} \rightarrow {}_yC_xH_z + {}_qC_xH_nO_k + CO + C$..2.1

After pyrolysis, there is an oxidation zone where the pyrolysis products move into the hotter zones of the gasifier. Air is introduced into the oxidation zone under starved oxygen conditions. The oxidation takes place at temperatures ranging from 700-1000℃ (Wei, 2005).

The principal oxidation reactions are presented in equation 2.2 - 2.5 (Reed, 1985; Bridgewater and Evans, 1993;EREN, 2002; Wei, 2005):

$C + O_2 \rightarrow CO_2 +$ Heat ……………………………………………….……………………2.2

$H_2 + 1/2O_2 \rightarrow H_2O +$Heat………………………………………………………………...2.3

$CO + 1/2O_2 \rightarrow CO_2 +$ Heat...2.4

$CH_4 + 3/2O_2 \rightarrow CO + 2H_2O$..2.5

The reaction products of the oxidation zone continually move into the reduction zone where there is insufficient oxygen, leading to reduction reactions between the hot gases and char. The principal reactions are presented in equation 2.6 - 2.8 (Krigmont, 1999; Wei, 2005; Kishore, 2008):

$CO_2 + C +$ Heat $\rightarrow 2CO$ 2.6

$C + H_2O +$ Heat $\rightarrow CO + H_2$..2.7

$CO + H_2O +$ Heat$\rightarrow CO_2 + H_2$...2.8

In reduction zone, the sensible heat of the gases and char is converted into the stored chemical energy in the syngas. Therefore, the temperature of the gases is reduced during this process (Wei, 2005).The final gas mixture consists of hydrogen, carbon oxides, water, tar/hydrocarbons and heavier hydrocarbons (Balat *et al.*, 2009). The gasification process is generally endothermic, which implies that it requires an energy input (Walker, 2006).

The generalized gasification reaction for wood may be written as given in equation (2.9) (Dayton, 2002):

$[CH_{1.44}O_{0.66}]\ n + H_2O + O_2 \rightarrow H_2 + CO + H_2O + CH_4 +$(tar/hydrocarbons) 2.9

The ratio of hydrogen or oxygen to carbon is almost constant in all wood types and the reaction equation can therefore be presented by the same formula (Walker, 2006).

2.6 Types of gasification reactors

Gasifiers are available in different types and sizes.These run on various types of feedstock including wood, straw, charcoal, coal, rice husks and agricultural wastes. Updraft (fixed bed) gasification systems are an old technology and were first installed in 1839 and used for coke and coal combustion. Before the Second World War, fluidized-bed wood gas generators were utilized to power combustion engines and automotive applications. Renewed interest in biomass gasification became evident after the energy crisis of the 1970s' (Overend, 2003). It is further reported that the biomass gasification technology was known as a relatively affordable alternative for small industrial power generations (Chopra and Jain, 2007). Gasifiers are classified by the way in which air, oxygen and/or steam is introduced into the system (Ciferno and Marano, 2002). The choice of one gasifier over another depends on factors such as the type of feedstock, its moisture content, ash content and finally the form of the fuel (Rajvanshi, 1986; Quaak*et al*., 1999). The three most common types of gasifiers are updraft, downdraft and the fluidized bed gasifier (Knoef, 2005; Walker, 2006).

A significant number of studies have been done on different types of gasifiers utilizing various kinds of biomass feedstock with the objective of improving the general understanding of the gasification process and to facilitate performance prediction of the units. Most of the studies demonstrated the phenomenological modeling and simulation of the gasification process (Rashidi, 1997; Ruggiero and Manfrida, 1999;De Jong *et al*., 2003;Giltrap *et al*.,2003; Khadse *et al*., 2004; Mitta *et al*., 2006; Sheth and Babu, 2006;Xiaodong *et al*., 2006;

Tinaut *et al*., 2008;Ratnadhariya and Channiwala, 2009) and the rest focus on experimental investigations (Zainal*et al*., 2002; Lv *et al*., 2004; Balamohan, 2008; Hsi*et al*., 2008).

2.6.1 Updraft gasifier

The updraft gasifier is also known as counter current gasifier (Figure 2.2). It is the simplest and oldest type of gasification reactor. It derived its name from the fashion in which the oxidant is fed through the reactor. The biomass fuel is loaded through the top into the reactor and moves downwards through the different stages of gasification through gravitational forces. The oxidant (usually air, oxygen or a mixture of air and steam) is fed from the bottom of the reactor, from where it moves upwards and gets in contact with the biomass. Combustion reactions occur at the bottom near the grate. Pyrolysis of the fuel occurs in the higher parts of the gasifier at temperatures between 350 – 800^{o}C, because the heat is transferred upwards from the lower combustion zones. In the pyrolysis zone, light gases, tars and solid char are formed. They are then further gasified in the reduction zone and result in light gases. The gases are collected from the top of the reactor. The remaining char is transferred to the combustion zone and completely combusted. Ash is then removed from the bottom of the system (Stultz and Kitto, 1992; Bridgwater and Evans,1993; Reed and Das, 1998).

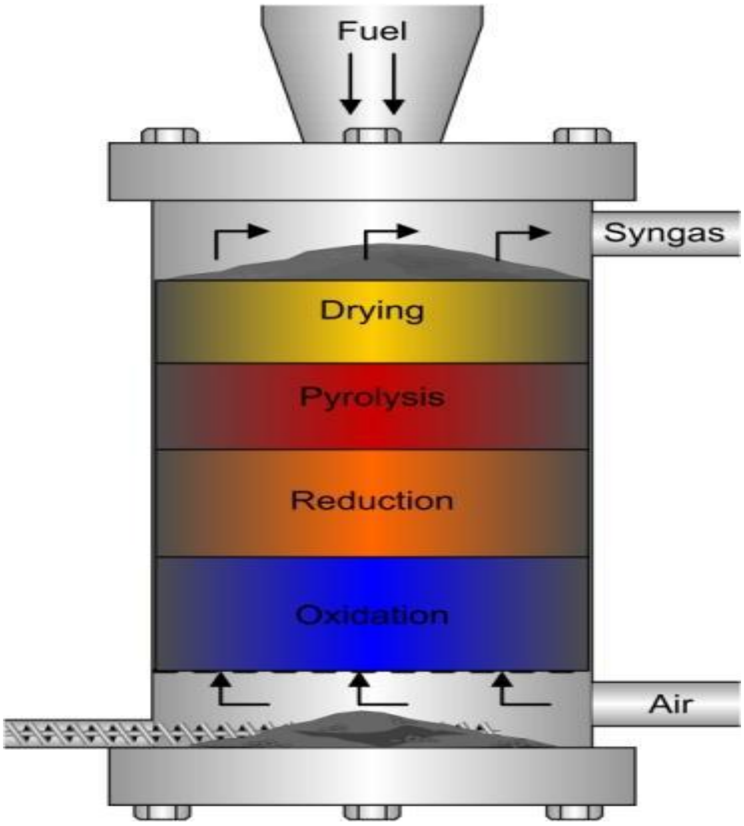

Figure 2.2: Up-draft biomass gasifier (Olofsson*et al*., 2005)

This type of a gasifier has numerous advantages. These include simplicity, easy internal heat exchange and high charcoal burnout. These qualities lead to high reactor efficiency, as well as compatibility to operate with many types of fuels (FAO, 2001). The reactor can operate with biomass having moisture content as high as 60 percent. The reactor typically yields producer gas with a calorific value of 1.80 to 3.33 MJ/kg, when oxidized with air. Oxygen as the oxidant in updraft gasification reactors produces higher calorific value gases of between 5 - 11 MJ/kg (Bridgewater, 1995). Milne and Evans(1998) found that the tar composition of the system is approximately 0.0050 to 0.0150 kg/m^3.

2.6.2 Downdraft gasifiers

The downdraft gasifier is also known as Co-Current Moving Bed (Figure 2.3). Its fuel is fed from the top and gravitates in the packed bed where it is gasified. Air, oxygen or a mixture of air and steam is fed either from the top or the middle of the reactor and the gasification zones are similar to the updraft reactor. The producer gas is, however, removed from the bottom part of the reactor. Devolatilization of the biomass occurs in the pyrolysis zone, which is heated by convection and radiation from the lower hearth zone, where temperatures reach 1200˚C. The hearth zone is embedded on top of the reduction zone, to which char is transferred and gasified (Brown, 2006).

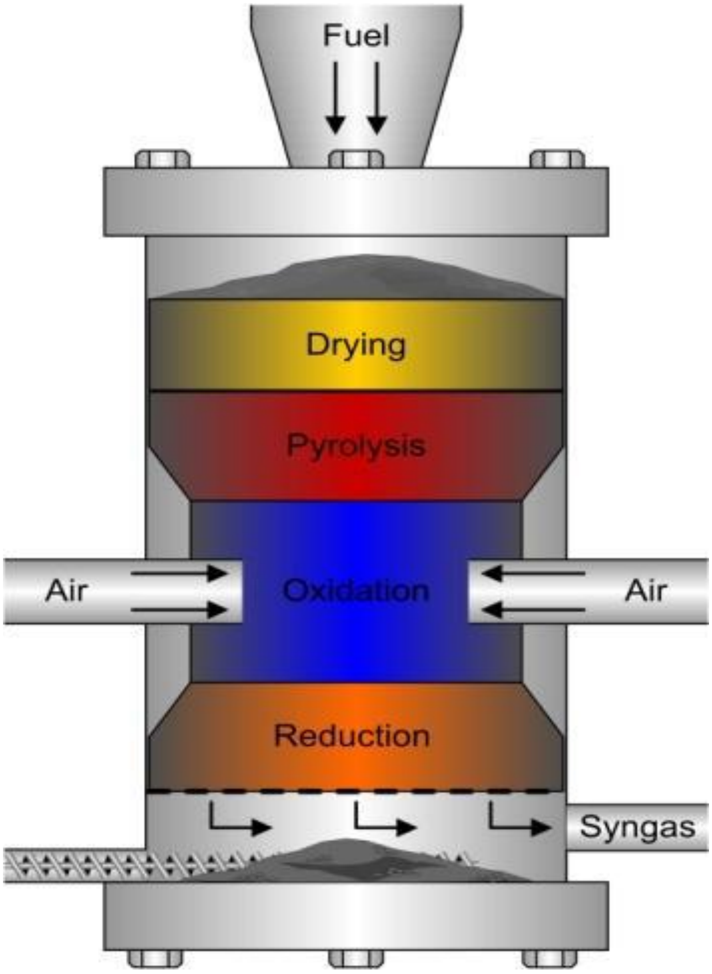

Figure 2.3: Down-draft biomass gasifier (Jorapur and Rajvanshi, 1997)

The producer gas obtained from a downdraft reactor contains less tar because the gasses are passed through the hot oxidation zone(Warnecke, 2000; Tatsiopoulos and Tolis, 2003). The breakdown of tars depends on the temperature of the oxidation zone and the residence time therein. The reactor requires fuel with a uniform size to prevent slagging and blocking. The type of oxidant used has strong effects on the calorific value of the fuel gas produced. Typically, the calorific value of the gas is about 1.80 to 3.33 MJ/kg aerated with air and roughly 6 - 7.1 MJ/kg when oxygen is used. The system produces tar with an amount of 0.0001-0.00025 kg/m^3 (Bridgewater, 1995).

2.6.3 Fluidized bed gasifier

The fuel is fed into or above the sand bed and the gasification agent is introduced from the bottom at speeds of 2-3 m/s which results in bubbles which travel up through the bed (Figure 2.4).The speed of the fluidizing agent is of great importance for the size and speeds of the bubbles and influences the mixing and heat exchange between the fuel particles. The sythesis gas is drawn off from the top of the reactor via a cyclone to separate sand and fly ash from the sythesis gas (Olofsson*et al*., 2005).

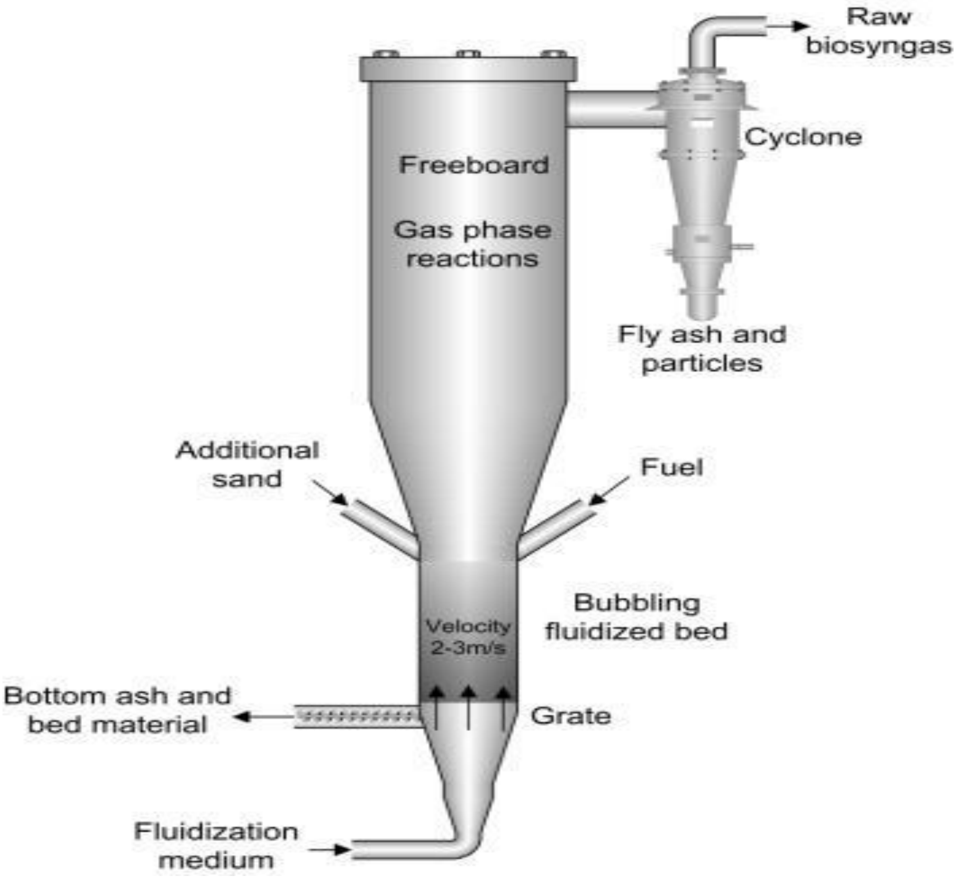

Figure 2.4: Fluidized-bed gasifier (Olofsson*et al*., 2005).

The fluidized bed reactor is composed ofa bed of small (1 to 5 mm) particles of suspended in air, steam or oxygen. Ingestion of biomass occurs into this bed in a temperature range of 700 – 900˚C. This peak temperature is reached through external heating of the bed. Fuel particles with the same size of 1 - 5 mm are fed into the reactor and spontaneously heated up to the bed temperature. This leads to a fast pyrolysis of the material, resulting in a mixture of components including producer gas. An internal cyclone prevents char from blowing out and re-circulates material back to the main reactor for conversion. Van der Aarsen(1982) reported that the major advantage of fluidised bed gasifiers is their feedstock flexibility, ease of temperature control, which can be maintained below the melting point of ash. They can be fed with finely milled biomass material, such as sawdust without any prior compression.

Fluidised bed gasifiers show a variety of benefits compared to the other reactor types, such as capability of handling large amounts of biomass feedstock, high temperatures and good mixing of the solid phase (Morris, 1998; Quaak *et al*.,1999). These properties offer uniform temperatures and an increased reaction rate, which leads to the production of consistent producer gas (Quaak *et al*.,1999). Disadvantages of the fluidised bed reactor includea high tar content (~ 0.0005 kg/m^3 gas) in the producer gas and a poor reaction to changes in fuel quantity and a slow carbon burnout. According to Bridgewater (1995) the energy content of the producer gas from fluidised bed gasifiers is similar to that of updraft reactors. It yields low to moderate calorific value producer gas, 0.4 - 0.6 MJ/kg with air as oxidant, 0.8- 1.43 MJ/kg with oxygen and 1.2- 2.04 MJ/kg when steam is used.

2.7Estimation of Biomass Synthesis Gas Composition Using Equilibrium Modeling

Conversion of biomass to biofuels and biopower has emerged as a promising alternative for meeting future energy demand. In addition, biomass is the only source of carbonbasedrenewable fuels thus proper and sustainable exploitation of this resource is essential to secure East Africa region. Biomass gasification has received enormous interest amongvarious biomass conversion technologies because it is almost feedstock-agnostic and can be usedto produce electricity and liquid fuels such as “green” gasoline and diesel using the FisherTropsch process.

The choice of biomass forgasification depends upon demographic factors. In the East Africa region, all countries have abundant forest residues, bagasse and agricultural waste. These biomass feedstocks vary in their composition, which ultimatelyaffects the synthesis gas composition. Most of the time, synthesis gascomposition is unknown until the gasification work is conducted. Experimental work is oftenresource-intensive (time and money) and a mathematical model predicting synthesis gas composition(concentration of H_2, CO, CH_4 and CO_2) using elemental analysis of biomass is helpful (Gopal, 2010).There are several models, for example thermodynamic equilibrium, kinetics-free, steady-state, semi-transient and transient, used to determine the synthesis gas composition (Reed, 1985).

Thermodynamic equilibrium model is the simplest of all type and gives synthesis gas composition for various biomass types at selected gasification temperatures with reasonable accuracy (Gopal, 2010). A system is said to be in thermodynamic equilibrium when it is in thermal, mechanical and chemical equilibrium. Chemical equilibrium is the state of minimum Gibbs free energy and maximum system entropy. Mechanical equilibrium occurs when the system is not performing or receiving any work. Thermodynamic equilibrium modeling provides a closer prediction when the reaction temperature is sufficiently higher (Zainal *et al*., 2001). Equilibrium conditions are difficult to achieve in practical operating conditions and results obtained from thermodynamic equilibrium modeling can serve as the maximum limit on synthesis gas composition. Synthesis gas composition and heating value of synthesis gas have been predicted using thermodynamic equilibrium modeling on biomass types and coal (Kinoshita *et al*., 1991; Mansaray *et al*., 2000; Mathieu and Dubuisson, 2002; Tang and Kitagawa, 2005; Jarungthammachote and Dutta 2007; Nikoo and Mahinpey, 2008; Huang and Ramaswamy, 2009; Hannula and Kurkela, 2010).

Watkinson *et al*. (1991)developed a thermodynamic equilibrium model and compared their result with various types of gasifiers used for coal. The study found the best prediction for entrained bed gasifier. The model showed a lower degree of accuracy in predicting syngas composition from fluidized bed and moving bed gasifiers. Jarungthammachote and Dutta (2007) and Melger *et al*.(2007)predicted synthesis gas composition from various biomass types using thermodynamic equilibrium modeling at a fixed ER. Their studies predicted gasification temperature through an iterative process and the synthesis gas composition at given equivalence ratio.

Gopal(2010) used thermodynamic equilibrium model equations 2.10 and 2.11 to compare his results with experimental results from Zainal *et al*.(2002), Bacaicoa *et al*.(1994), Jayah *et al*. (2003) and Altekini *et al*.(2003).

$\mathrm{H_2(percent\ vol.)} = 0.223\mathrm{C} + 1.022\mathrm{H} + 0.332\mathrm{O} - 15.36$ ………………...2.10

$\mathrm{CO(percent\ vol.)} = 0.71\mathrm{C} - 1.35\mathrm{H} + 0.47\mathrm{O} - 22.43$ …………………..….2.11

$\mathrm{CO_2(percent\ vol.)} = -0.41\mathrm{C} - 0.04\mathrm{O} + 31.65\ (\mathrm{R^2\ value} = 0.96)$ ……..2.13

H_2 and CO composition as reported by Zainal *et al*. (2002) was the average of 57 test runs with the temperature around 700 – 900 °C for most of the experimental duration. They used furniture wood as their feedstock with equivalence ratio of between 0.268-0.43. H_2 and CO data from Bacaicoa *et al.* (1994) was from experiment conducted in the downdraft gasifier with capacity of 25-50 kg/hr and equivalence ratio of 0.247. The data taken from Jayah *et al.* (2003) was among one of their conducted experiments in the downdraft gasifier. The syngas reported by Jayah *et al.* (2003) was between 18.4-22.1% of CO and 13-18.3% of H_2 with the temperature of the gasification zone in the range of 700 – 1000 °C. Comparison for both Bacaicoa *et al.* (1994) and Jayah *et al.* (2003) was done with syngas composition at temperature close to this model. CO and H_2 composition from Altafini *et al.* (2003) was average of 10 test runs with the reaction temperature around 832 °C and average air/sawdust ratio of 1.829. The predicted result in table 2.4shows a good agreement with the experimental resultsof Gopal(2010).

Table 2.4 Comparison of model with experimental values

Moisture content, Wt % (wet basis)	Ultimate analysis, Wt (dry basis)			H_2, % vol. (moisture free basis)		CO, % vol. (moisture free basis)		References
	C	H	O	P	E	P	E	
0	47.3	5.8	45	16.1	14.05	24.5	24.04	Zainal *et al.*,2002
12	45.8	6	47.9	17.8	15.07	22.3	24.1	Bacaicoa*et al.*,1994
14	50.6	6.5	42	17.6	18.3	22	20.2	Jayah *et al.*, 2003
20	52	6.1	41.6	17.8	14	22.2	20.14	Altafini *et al.*, 2003

Where P is values predicted from equation 2.10-2.11 for H_2 and CO respectively. E is values from Experimental data.

Chen (1987) developed a simulation model for the prediction of synthesis gas. The model was later adjusted by Jahah (2002) to suit downdraft gasifiers. The prime objectives of Chen’s model were to project and estimate parameters of a downdraft gasifier, such as its reactor diameter, length and size of the gasification zone. The model was also developed to investigate the effect of other operating parameters such as fuel/feedstock size, moisture content, elemental composition, input air temperature and gasifier load per run on the reactor performance. The gas output results obtained from Chen's model were comparable with other literature experiments presented by Graham and Huffman (1981) for industrial scale downdraft biomass gasifiers. A comparative review of predicted gas composition from Chen's model and typical experimental results presented by Graham and Huffman (1981) is given in Table 2.5. Chen's model is thus applicable for the simulation of biomass performance in downdraft gasifiers.

Table 2.5 Comparative results of Chen's model with Graham and Huffman

Gas composition (% volume)	Chen's model	Typical range reported by Graham and Huffman (1981)
CO	18.5	11.9-26.3
H_2	15.8	8.9-18.0
CO_2	12.8	9.1-17.7
N_2	48.7	41.5-54.7
CH_4	2.6	2.1-3.5
Trace	1.6	1.5-2.6

Banapurmath *et al.*(2009) reported 19 % ± 3 % CO and 18 % ± 2 % H_2 in a downdraft biomass gasifier which they used to produce approximately 17MWth electricity. Chawdhury and Mahkamov(2010) investigated the production of syngas from wood pellets and discovered the production of CO was between 19 to 22 % and the production of H_2 was between 12 to 19 %.

CHAPTER THREE

METHOD AND MATERIALS

3.1 Study Area

The study was conducted around the lake Victoria Basin in Kenya and Uganda. In Kenya eight regions were chosen namely Malava forest in Kakamega county, Kibiri block forest in Vihiga County, Ombo forest in Migori county, Kodera forest in Rachuonyo county, Kakamega Forest in Kakamega County, Port Victoria natural forest in Busia county, Aloso block forest in Migori county and Sony sugar companyin Migori county.

Kakamega Forest (KF) lies between 0°10́N-0°21́N and 34°48́-34°58́E.Malava forest lies between 0º 28' 0N and34°51' 0 E(Appendix III). Kodera forest liesbetween 0°33’0" E and 34° 40’0".Kibiri Block is located in (00º 10’ 06"N and 34º 51’ 40"E. Sony sugar company lies between 0°53'43"N and 34°31'53"E. Aloso block forest lies between 36° 13"N and 3° 55"E. Ombo forest lies between 36° 13"N and 3° 55"E. Port Victoria forest lies between 00º 27’ 11"N and 34º 07’ 30"E. In Uganda, Wakiso district was chosen and lies between 00° 24N and 32° 29E.Forests were purposely selected because permission was granted by the Kenya Forest Service to access state of forest to undertake sampling and biomass resource survey. Similar sampling was done in Wakiso district in Uganda.

3.2 Sampling Procedure and Collection

Breast height (1.3 metres from the ground) stem wood samples were collected from each species. *Cupressus lustitanica*from Kakamega forest, Ombo forest, Kodera forest and Port Victoria forest, *Pinus patula*from Kibiri block forest and Kodera forest, *Pinus caribaea*from Kodera forest and Wakiso forest, *Calitris robusta*from Aloso block forest and *Eucalyptus grandis*from Wakiso forest. The sample was cut into small wood chips.

Sugarcane bagasse was sampled from top, middle and bottom of the heap of sugarcane baggase damping site in South Nyanza Sugar factory, Kenya. The samples were placed in three 50kg gunny sacks.

3.3 Proximate Analysis

3.3.1 Determinationof Moisture content

The moisture content was determined in accordance to ASTM Standard D 3173-87(1998). Ceramic weighing dishes were pre-dried by placing them in a drying oven at 105±3 ºC for four hours. The pre-dried dish was then weighed to the nearest 0.1mg. The tree trunk was cut into 2cm round disks. The disk was then cut horizontally to provide the sample. The tree trunk approximately 20 g was weighed to the nearest 0.1 mg.

For sugarcane bagasse, the particles were small and therefore were weighed into 20 g. For each feedstock nine samples were used. The sample was then placed in a convection oven at 105±3 ºC for four hours. The sample was then removed from the oven to cool to room temperature in desiccators with P_2O_5 as drying agent. The crucibe containing the oven dried sample was weighed and the weight recorded. The sample was placed back into the convection oven at 105±3 ºC and dried to constant weight. Percentage weight loss was taken as moisture content of the sample.The moisture content was calculated using equation 3.0

$$\%\,\mathrm{MC} = 100 - \left[\left(\frac{\mathrm{Weight}_{\mathrm{drycrucible\ \ +dry\ sample}} - \mathrm{Weight}_{\mathrm{dry\ crucible}}}{\mathrm{Weight}_{\mathrm{Sample\ \ as\ received}}}\right) \times 100\right] \ldots\ldots\ldots\ldots\ldots 3.0$$

3.3.2Ash Determination

The ash determination was done in accordance withASTM Standard D 3174-97 (1998).Two centimeter round disks wood sample and sugarcane bagassewere dried to a constant weight at 105 ºCin the oven and placed in the desiccators. A porcelain marker was used to mark nine crucibles with identifiers. The crucibles were weighed. 10 g samplewere placedinto the nine crucibles and placed in the furnace set to 575±25ºC for four hours, after which the crucibles were cooled in the desiccators. The weight of the crucible and the sample was then recorded to the nearest 0.1mg.For each feedstock nine samples were used. The ash content was calculated using equation 3.1

$$\text{Ash percent} = \frac{W_3 - W_1}{W_2 - W_1} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3.1$$

Where W_1 is mass of empty dry crucible, W_2 is mass of dry crucible plus dry sample of biomass and W_3 is mass of dry crucible plus cooled grayish white ash.

3.3.3Volatile determination

The volatile matter determination was done in accordance to ASTM(1999).Approximately 10 g of the dried sample were weighed into crucibles with a closely fitting cover and placed into a muffle furnace maintained at 950°C±20°C. The crucibles were left for exactly 7 minutes.They were then removed, cooled in the desiccators and weighed. Nine sample of each feedstock were used.Volatile matter was calculated using equation 3.5

Volatile Matter(VM) percent =100 x (I g – F g)/I g……………………………………3.2

Where I g was the initial weight of the sample and F g final weight of the sample.

3.3.4 Calculation of Percentage Fixed Carbon

Fixed carbon (FC) was calculated by difference from VM and ash amount according to Mckendry (2002). Thus FC was calculated using equation 3.3

$$\% \text{ FC} = 100 - (\% \text{ VM} + \% \text{ Ash}) \quad \ldots\ldots 3.3$$

Where FC was fixed carbon and VM was volatile matter

3.4 Energy Content

The energy content was determined in accordance to ASTM D2015-96 standard (1998). Feedstocksamples were dried to constant weight at 105 ºC inan oven and placed in the desiccators to cool. Hammer mill was used to grind dried samples. The ground samples were made into briquette of approximately one gram. A Gallenkamp Auto bomb calorimeter model number SG97/10/070 was used. One gram of briquetted sample was taken in a nicrom crucible. A 9 cm long cotton thread was placed over the sample in the crucible to facilitate in the ignition. Both the electrodes of the calorimeter were connected by a nicrom fuse wire. The bomb was immersed in a 3 liters waterjacket. The bomb was filled with oxygen at a pressure of 30 psi. The surrounding 3 liters water jacket was continually stirred to equilibrate the temperature. The sample was fired with the help of an electric source to produce a spark inside the bomb which combusted the fuel. A thermometer attached to the water jacket recorded any change in temperature due to the burning of the feedstock. Gross heat was calculated by using a template provided by Gallenkamp Auto bomb calorimeter.

3.5 High Heat Values Derived from Theoretical Equations

Equations 3.4 – 3.6 were used to estimate the higher heating values of biomass samples and the results compared with the experimental ones.

Demirbas (1997) HHV= 0.196 x FC + 14.119 ……………………………………… 3.4

Tilman (1978) HHV= 0.4373 x C - 1.6701 ……………………………………… 3.5

Jenkins and Ebeling (1985) HHV= -0.763+0.301 x C + 0.525 x H + 0.064 x O………3.6

3.6 Ultimate Analysis

The carbon, nitrogen and hydrogen content was determined using flash 2000 Elemental analyzer model number 31712052 according to ASTM E775-8 standard (1998). Dry sample were ground into a fine powder and weighed into 2 mg on tin foil and placed into elemental furnace. The 2 mg sample was subjected into complete combustion. The sample was burned in a combustion chamber in oxygen atmosphere with helium as a carrier gas. The combustion gases released are CO_2, H_2O, NO, NO_2 and N_2. NO and NO_2 were reduced at copper contact to N_2. H_2O and CO_2 were captured in different adsorption columns. N_2 was not captured by the columns and was detected first by a thermal conductivity detector (TCD). H_2O and CO_2 were released consecutively and sent to the TCD. Mass percentage was then determined integrally. From the known sample weight, the C, H and N content was determined. The elemental analyzer was connected to the computer which gave subsequent measurement of carbon, nitrogen and hydrogen percentage.

3.9Calculations for Synthesis Gas Composition

The equations 3.7 - 3.9 developed by Gopal (2010) were used to predict the percentage volume of CO, CO_2, and H_2.

$$\mathrm{CO_2(percent\ vol.)} = -0.41\mathrm{C} - 0.04\mathrm{O} + 31.65\ (\mathrm{R}^2\ \mathrm{value} = 0.96) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

$$\mathrm{H_2(percent\ vol.)} = 0.223\mathrm{C} + 1.022\mathrm{H} + 0.332\mathrm{O} - 15.36\ (\mathrm{R}^2\ \mathrm{value} = 0.99) \ldots\ldots\ldots 3.8$$

$$\mathrm{CO(percent\ vol.)} = 0.71\mathrm{C} - 1.35\mathrm{H} + 0.47\mathrm{O} - 22.43\ (\mathrm{R}^2\ \mathrm{value} = 0.98) \ldots\ldots\ldots\ldots 3.9$$

3.9 Data analysis

The data obtained from the study was subjected to statistical analysis including the mean, one way ANOVA, standard deviation and Student-Newman-Keuls (SNK). The methods are useful in providing interdependence of the variables and significant differences (Miller and Miller, 1988).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Six different biomass feedstocks were analyzed for their differentproximate,ultimate and heating properties. These analyses helped in assessing their suitability to be used as gasification fuel. This chapter discusses the results for six different biomass feedstock namely *Pinus caribaea, Calitris robusta, Cupressus lustitanica, Eucalyptus grandis, Pinus patula* and sugarcane bagasse from different regions in LVB. The result obtained from ultimate analysis was also used to predict synthesis gas composition for the various biomass feedstocks.

4.2 Proximate Analysis.

The results of the proximate analysis carried out on *Pinuscaribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis, Pinus patula* and Sugarcane bagasse are presented in table 4.1.

Table 4.1Proximate analysis of some biomass fuels in the LVB, weight percentage dry basis

Fuel type n=9	% Moisture (Mean ± SE)	% Ash content (Mean± SE)	% VM (Mean± SE)	% FC (Mean± SE)
Pinus caribaea	56.69±0.32^{d}	0.38±0.02^{a}	76.98±0.61^{b}	22.64±0.63^{d}
Calitris robusta	48.64±0.28^{c}	0.54±0.02^{a}	78.79±0.61^{b}	20.67±0.63^{b}
Cupressus lusitanica	39.11±3.24^{b}	0.58±0.05^{a}	74.68±0.49^{a}	24.74±0.54^{e}
Eucalyptus grandis	48.59±0.43^{c}	0.42±0.02^{a}	78.24±0.25^{b}	21.34±0.27^{bc}
Pinus patula	25.74±1.54^{a}	0.39±0.05^{a}	77.57±0.23^{b}	22.04±0.28^{cd}
Sugar cane bagasse	36.47±0.32^{b}	2.94±0.14^{b}	77.57±0.23^{b}	14.35±0.33^{a}
p-value	< 0.0001	< 0.0001	< 0.0001	<0.001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

4.2.1 Moisture Content.

Table 4.1 showsthat the moisture content of the six biomass samples has significance difference since ($p < 0.05$, SNK-test).*Pinus caribaea* showed the highest amount of moisture content of 56.69±0.32 % while *Pinus patula* showed the lowestof 25.74±1.54 %. There was no significance difference between *Calitris robusta* and *Eucalyptus grandis* since their moisture content were48.64±0.28 %and 48.59±0.43 % respectively (SNK-test). Also, *Cupressus lusitanica* and Sugar cane bagasse showed no significance difference from one another (SNK-test). The moisture content of the six fuels waswithin acceptable range for gasifiers.

The moisture percentage range of wood varies between 10and60 while that of sugarcane bagasse is between 40and60 (Faaij *et al*., 1997; Quaak *et al*., 1999). The moisture content of*Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus Patula* were in the range of 10 to 60 %. Also sugar cane bagasse was in the range of 40 to 60% (Faaij *et al*., 1997; Quaak *et al*., 1999).

Moisture content is the easiest to vary since biomass fuel can be dried and used in any type of gasifier. Brammer and Bridgewater (1999) reported that moisture content up to 20% and 50% are acceptable to downdraft and updraft gasifiers respectively. On the other hand, fluidized bed gasifiers have been reported to gasify higher moisture content materials, up to 70% (Holmbergy and Ahtila, 2004). Table 4.1 shows that no biomass fuel can be used for downdraft gasifier unless it is first dried. *Calitris robusta, Cupressus lusitanica, Eucalyptus grandis, Pinus patula* and Sugarcane bagasse can be used in updraft gasifier except *Pinuscaribaea*since they contain less than 50 % moisture. The six biomass fuels can be used influidized bed gasifiers since they contain less than 70 % moisture.Moisture content of biomass species varies from one region to another. This is because the same species are planted in different soil with varying water content and areas with different seasons. A comparison of percentage moisturecontent in selected regions in the LVB is shown in table 4.2 for *Cupressus lustanica* and *Pinus patula*.

Table 4.2 Comparison of percentage moisture content in selected regions in the LVB for *Cupressus lusitanica*and *Pinus patula*

Species	Region	% moisture content (Mean ± SE), n= 9	p-value
Cupressus lusitanica	Ombo Kodera	47.95±0.25 34.69±4.54	0.01
Pinus patula	Kibiri Kodera	23.20±0.12 30.85±2.58	0.006

*Cupressus lusitanica*and *Pinus patula*showed significance difference in moisture content ($p < 0.05$, T-test). *Cupressus lusitanica* in Ombo forest shows higher moisture content compared to Kodera forest. Also, *Pinus patula* in Kodera forest has higher moisture content than in Kibiri forest.This is because of different climate, ecology and soil.

4.2.2 Ash Content

Table 4.3 shows the percentage ash content in the six biomass fuels. There was significant difference in the percentage ash content since ($p <0.05$, SNK-test).

Table 4.3The percentage ash content of biomass fuels

Biomass fuel	% Ash content (Mean ± SE) n= 9
Pinus caribaea	0.38 ± 0.02^{a}
Calitris robusta	0.54 ± 0.02^{a}
Cupressus lusitanica	0.58 ± 0.05^{a}
Eucalyptus grandis	0.42 ± 0.02^{a}
Pinus patula	0.39 ± 0.05^{a}
Sugarcane bagasse	2.94 ± 0.14^{b}
p-value	< 0.0001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Sugarcane bagasse showed significantly higher level of ash compared to *Pinus caribaea,calitris robusta,Cupressus lusitanica,Eucalyptus grandis* and *Pinus patula.* Thisis shown clearly on the figure in appendix 1.The six biomass qualifies to be used in biomass gasification as they showed less than 5 % ash content (FAO, 1986). All the biomass feedstock investigated can be used in downdraught gasifier as they contained less than 6% according to (Van Swaay *et al.*, 1994; BTG, 1995), although sugarcane bagasse can be used in updraft gasifier as the minimum percentage is 1.4 % ash and maximum of 25% (Van Swaay *et al,* 1994; BTG, 1995).The percent ash content of sugarcane bagasse 2.94±0.14 was in agreement with Sun*et al*. (2004) who reported 2.3 %. Lv *et al*. (2004) used pine and reported ash content of 0.55% which was higher compared to *Pinus caribaea*and *Pinus patula* in table 4.3 which showed 0.38±0.02% and 0.39±0.05% respectively. Quaak *et al*.(1999) reported that typical wood have ash of 0.25-1.7 % which were in agreement with *Pinus caribaea*,C*alitris robusta,Cupressus lusitanica,Eucalyptus grandis* and *Pinus patula*. Also Quaak *et al*.(1999) reported that ash content of sugarcane bagasse ranges from 1.7-3.8 % which agrees with sugarcane bagasse in the study.

Ash content varies from same species in different region in the LVB. This is can be attributed to different soil nutrients(FAO, 1986). Figure 4.1 shows significance difference in ash for *Pinus patula* in Kibiri and Kodera. Kodera shows higher percentage ash content compared to Kibiri.

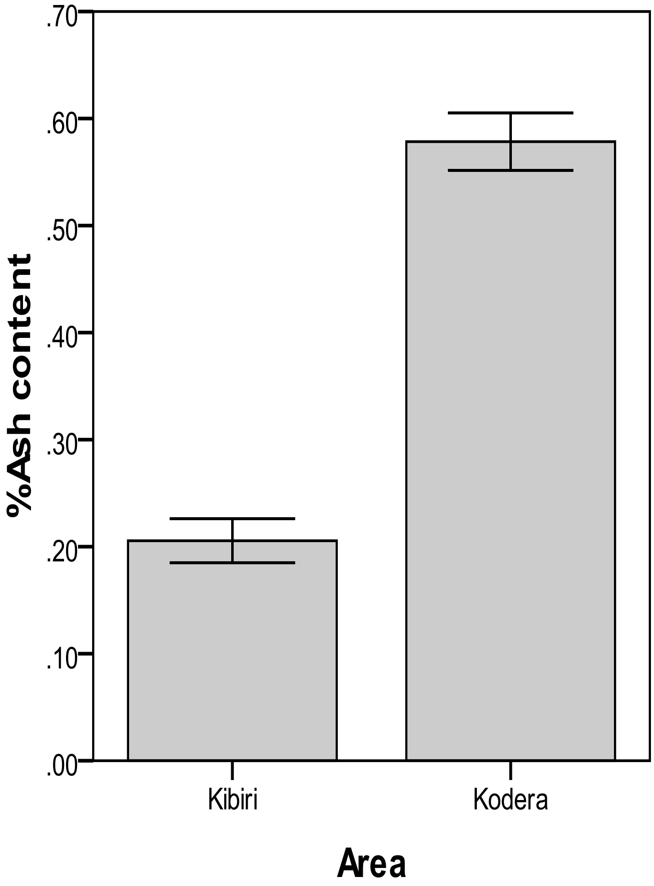

Figure 4.1 Ash content in Kibiri and Kodera for *pinus patula*

4.2.3 Volatile Matter (VM)

The percentages VM are shown in the table 4.4 and appendix 11. The result in 4.4 shows significant difference since ($p < 0.05$, SNK-test).

Table 4.4Percentage weight ofvolatile matter of six biomass fuel

Biomass fuel	% volatiles matter (Mean ± SE) n= 9
Pinus caribaea	76.98±0.61^{b}
Calitris robusta	78.79±0.61^{b}
Cupressus lusitanica	74.68±0.49^{a}
Eucalyptus grandis	78.24±0.25^{b}
Pinus patula	77.57±0.23^{b}
Sugarcane bagasse	82.71±0.19^{c}
p-value	< 0.0001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Sugarcane bagasse sample has the highest percentage mean of volatile matter compared to percentage mean of*Cupressus lusitanica*. The percentage of volatile matter of *Pinus caribaea, Calitris robusta, Eucalyptus grandis* and *Pinus patula* did not differ significantly from one another (SNK-test). Lv *et al.* (2004), Higman and Burgt (2003) andDemirbas (2003) showed that *Pinus caribaea* and *Pinus patula* have volatile matter of around 74.5%. This percentage is close to the result obtained in this work. According to Wood Gas as Engine Fuel (1986) and Turare (2002) woods have volatile matter of 72to78 %. These percentages agree with the values of *Pinus caribaea*,*Calitris robusta*,*Cupressus lusitanica*,*Eucalyptus grandis* and *Pinus patula*.

4.2.4 Fixed Carbon (FC)

The percentage of fixed carbon is shown in the table 4.5. The result shows significance difference ($p < 0.05$, SNK-test).

Table 4.5 Percentage weight of fixed carbon

Fuel type	N	% fixed carbon n= 9
Pinus caribaea	36	22.64 ± 0.63^{d}
Calitris robusta	9	20.67 ± 0.63^{b}
Cupressus lusitanica	27	24.74 ± 0.54^{e}
Eucalyptus grandis	90	21.34 ± 0.27^{bc}
Pinus patula	18	22.04 ± 0.28^{cd}
Sugarcane bagasse	27	14.35 ± 0.33^{a}
p-value	-	<0.001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Cupressus lusitanica showed highest fixed carbon compared to sugarcane bagasse.Sugarcane bagasse showed the lowest fixed carbon. *Pinus Caribaea*and *Pinus patula* did not show statistical difference from one another (SNK-test). Wood averages around 20 % fixed carbon

The results for fixed carbon for *Pinuscaribaea,Calitris robusta,Cupressus lusitanica,Eucalyptus grandis* and *Pinus patula*were slightly higher than the average wood FC which is around 20 % according to Mckendry (2002).Anjireddy and Sastry (2011) showed that sugarcane bagasse had 15.8 % fixed carbon which was higher than the result in this work. Generally the six biomass sample showed high fixed carbon which is good for gasification process.

4.3 Energy Content

The table 4.6 shows the energy content of the fuels among the six biomass fuel in the LVB.

Table 4.6 Energy content of the fuels among the species in LVB

Fuel type	Energy (Mean ± SE) MJ/Kg, n= 9
Pinus caribaea	18.61±0.12^b
Calitris robusta	18.39±0.08^b
Cupressus lusitanica	19.13±0.13^c
Eucalyptus grandis	17.44±0.04^a
Pinus patula	19.48±0.42^c
Sugarcane Bagasse	16.95±0.10^a
p-value	< 0.0001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Table 4.6 shows a significant difference of energy content of fuel among the six biomass fuel since ($p < 0.05$, SNK test). *Pinus patula* and *Cupressus lusitanica* recorded higher energy content compared to *Eucalyptus grandis* and Sugarcane Bagasse.*Pinus caribaea*and *Calitris robusta* did not show significant difference from one another.

Nonde (2009) suggested that *Eucalyptus grandis is*the most suitable species as feedstock in wood feedstock gasifiers. This is because these coppices well, have moderate to fast growth rates and have high calorific value ranging from 18 to 20 MJ/Kg. *Eucalyptus grandis* showed slightly less calorific values of 17.44 ± 0.04 MJ/Kg compared with those obtained by Nonde (2009). But the result of *Eucalyyptus grandis* was in agreement with those obtained by Quaak (1999). The results obtained by Kishore(2008) for *Eucalyptus grandis* was 18.64 MJ/Kg which were slightly higher compared to result for *Eucalyptus grandis* in table 4.6 which was 17.44 MJ/Kg. *Pinus patula* showed 19.48 ± 0.42 MJ/Kg which were in agreement with Hakkila and Verhasalo (2009) who reported 19.3 MJ/Kg.

4.4High Heat Values Derived from Theoretical Equations

The predicted high heat values of biomass samples using equations 3.2 – 3.4 and their measured heat values are presented in Table 4.7

Table 4.7Measured and predicted higher heat values (MJ/kg) of samples.

Fuel type n = 9	Measured heat value (MJ/kg	Predicted HHV (MJ/KG		
		Demirbas (1997)	Tilman (1978)	Jenkins and Ebeling (1985)
Pinus caribaea	18.61±0.12^{b}	18.56±0.52^{b}	18.26±0.11^{b}	18.93±0.12^{b}
Calitris robusta	18.39±0.08^{b}	18.17±0.55^{b}	18.99±0.09^{c}	19.39±0.11^{b}
Cupressus lusitanica	17.44±0.04^{a}	18.97±0.41^{b}	19.70±0.13^{c}	19.60±0.16^{b}
Eucalyptus grandis	19.13±0.13^{c}	18.30±0.23^{b}	18.23±0.15^{c}	18.97±0.09^{b}
Pinus patula	19.48±0.42^{c}	18.44±0.23^{b}	19.25±0.69^{c}	19.54±0.41^{b}
Sugarcane Bagasse	16.95±0.10^{a}	16.93±0.39^{a}	16.02±0.26^{a}	17.20±0.17^{a}
p-value	< 0.0001	<0.001	<0.001	<0.001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Demirbas (1997) that utilized fixed carbon predicted values that are closer to the measured values. Tilman (1978) who used carbon content, the values were also close. Jenkins and Ebeling (1985) who used carbon, hydrogen and oxygen content, the value were slightly higher than the measured values. The predicted HHV showed that they can be used alone when the information about the proximate and ultimate analysis are available. The predicted HHV can also be used counter check the errors on the bomb calorimeter and viceversa. These equations provide a way for a rapid, easy and cheap estimation of the HHV which may be of particular interest in those contexts where sophisticated and expensive equipments for experimental HHV measurement and sometimes this equipment are not always available.

4.5 Ultimate Analysis

Table 4.8 shows the mean percentages of nitrogen, carbon, hydrogen and oxygen in the six biomass feedstocks.

Table 4.8: The Mean Percentage Weight of N, C, H and O of Six Biomass Fuel in the LVB.

Fuel type n=9	% Nitrogen (Mean ± SE)	% Carbon (Mean± SE)	% Hydrogen (Mean± SE)	% Oxygen (Mean± SE)
Pinus caribaea	0.25±0.07	45.57 ± 0.26^{b}	5.44 ± 0.22^{b}	48.36 ± 0.35^{c}
Calitris robusta	0.18±0.01	47.26 ± 0.21^{bc}	5.56 ± 0.17^{b}	46.46 ± 0.27^{b}
Cupressus lusitanica	0.07±0.02	48.88 ± 0.29^{c}	5.17 ± 0.34^{b}	45.46 ± 0.45^{b}
Eucalyptus grandis	0.17±0.02	45.50 ± 0.35^{b}	5.55 ± 0.13^{b}	48.39 ± 0.37^{c}
Pinus patula	0.22±0.04	47.84 ± 1.57^{bc}	5.59 ± 0.18^{b}	43.41 ± 1.58^{a}
Sugar cane bagasse	0.23±0.04	40.45 ± 0.61^{a}	4.32 ± 0.13^{a}	51.1 ± 0.64^{c}
p-value	< 0.056	< 0.0001	< 0.0003	<0.001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

4.5.1 Percentage Weight of Nitrogen

Table 4.8 shows the percentage weight of nitrogen of the six biomass feedstock. The mean percentage of nitrogen did not differ significantly since ($p > 0.05$, SNK-test). The six biomass samples had low nitrogen content compared to fossil fuels. Burning fossil fuels, accounts for 25 percent of nitrogen inputs (Helsinki Commission, Baltic Marine Environment Commission, 2005).This makes the six biomass species very interesting from the energetic standpoint since nitrogen oxides (NO_x) negatively affect the facilities and the environment. Nitrogen oxides are causes of acid rains. The percentage N of sugarcane bagasse reported by Jenkins *et al*.(1998) was 0.16%. This was low compared to 0.23% in this study.

Demirbas(2004)found nitrogen in sugarcane bagasse to be 0.38% which is in agreement with this work.

Higman and van der Burgt(2003) found that a typical wood sample have 0.3 % nitrogen content which is slightly higher than the result of *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula*obtained in this work. All biomass material according to Jenkins *et al*. (1998) contains 0.2 to 1% nitrogen content. The six biomass samples contained less than 1 %, which agrees with the result.

Some studies (Leckner and Karlsson, 1993; Obernberger, 1998;Johansson *et al.*, 2004) revealed a strong dependency between the nitrogen content of the fuel and the formation of NOx during combustion. All shows that an increase of fuel-N results in higher levels of NOx into the atmosphere (Demirbas, 2004; Carvalho *et al*., 2007). To avoid emission of NOx to the atmosphere during combustion, all biomass material according to Obernberger *et al*.(2006) must contain less than 0.6 % nitrogen. NOx has adverse effects on both human health and environment. NOx can cause irritation to the eye, throat, nausea and headache. When they come into contact with rain water droplets, NOxdecomposes and produce nitrous acid and nitric acid which contribute to acid rains that damage buildings, agricultural crops, and kill aquatic organisms. Likewise, NOx can also react with volatile organic compounds (VOCs) under presence of sunlight to form smog (ground level ozone)—that can trigger millions of asthma attacks (Baukal *et al.*, 2001).The six biomass samples from the study contained less than 0.6 % which qualifies them as suitable feedstock for gasification processes.

A comparison of percentage of nitrogen in selected regions in the LVB is shown in table 4.9 for *Cupressus lustanica, Pinus caribaea*and *Pinus patula.*

Table 4.9 Comparison of percentage of Nitrogen in Selected Regions in the LVB for *Cupressus lusitanica, Pinus caribaea*and *Pinus patula*

Biomass fuel	Region	% Nitrogen (Mean ± SE), n= 9	p-value
Cupressus lusitanica	Kakamega Kodera Ombo Port Victoria	0.16 ± 0.00^{b} 0.02 ± 0.01^{a} 0.05 ± 0.03^{a} 0.04 ± 0.01^{a}	0.001
Pinus caribaea	Kodera Wakiso	0.16±0.04 0.27±0.08	0.516
Pinus patula	Kibiri Kodera	0.05±0.00 0.31±0.02	< 0.0001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Table 4.9 shows that *Cupressus lusitanica* in Kakamega region have significantly higher percentage nitrogen compared to Kodera, Ombo and Port Victoria (SNK-test). *Pinus caribea* showed no significant difference in percentage nitrogen in Kodera and Wakiso ($p > 0.05$, T-test). *Pinus patula* showed significance difference in percentage nitrogen in Kibiri and Kodera ($p< 0.05$, T-test). This variation in the percentage nitrogen between the regions and species is because of different environmental factors, nutrients and water between plants (Michagan Forest Forever Teacher Guide, 1998).

4.5.2 Percentage Weight of Carbon

The percentage weight of carbon in the six samples is presented in table 4.8. The results show a significance difference of percentage weight of carbon among the six biomass fuel since ($p < 0.05$, SNK test). The percentage mean of *Cupressus lusitanica, Calitris robusta* and *Pinus patula* showed significantly higher level of carbon compared to sugarcane bagasse. *Pinus* *caribaea, Eucalyptus grandis, Pinus patula* and *Calitris robusta* did not show significant difference from one another (SNK-test). Figure 4.2 shows the variation of percentage carbon among different species. Sugarcane bagasse showed slightly lower % C of 40.45±0.61 compared with the one reported by Jenkins *et al*. (1998) who reported 48.64%. According to Demirbas (2004) and BTG (1987) carbon content for typical biomass must range from 42-54 %. *Pinus caribaea,Eucalyptus grandis,Pinus patula,Cupressus lusitanica* and *Calitris robusta* were within this range except sugarcane bagasse which had lower percentage of carbon of 40.45±0.61%. Sugarcane bagasse had lower percentage carbon compared with that of Demirbas (2004) who reported 44.80%. Also, Grover (1989) found that sugarcane bagasse had carbon content of 44.1 % which was slightly higher with the result. Raveendran *et al*. (1995) reported similar result of sugarcane bagasse.

The higher the carbon content of biomass sample, the higher the heating values. *Pinus caribaea,Eucalyptus grandis,Pinus patula,Cupressus lusitanica* and *Calitris robusta* have high carbon content hence higher heating value than sugarcane bagasse which had low carbon content (Fengel and Wegener, 1984; Ragland *et al*.,1991; Huhtinen, 2005; Demirbas and Demirbas, 2009).

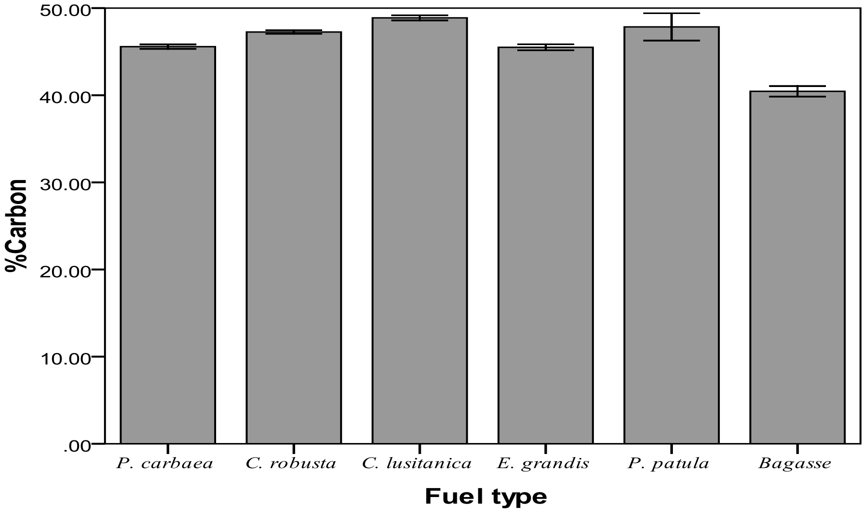

Figure 4.2The percentage carbon of different fuel from LVB.

A comparison of percentage of carbon in selected regions in the LVB is shown in table 4.10 for *Cupressus lustanica, Pinus caribaea*and *Pinus patula.*

Table 4.10 Comparison of percentage Weight of Carbon in Selected Regions in the LVB for *Cupressus lusitanica, Pinus Caribaea*and *Pinus patula*

Species	Region	% Carbon (Mean ± SE), n= 9	p-value
Cupressus lusitanica	Kakamega Kodera Ombo Port Victoria	49.09 ± 0.16^{ab} 47.96 ± 0.75^{a} 49.99 ± 0.39^{b} 48.46 ± 0.00^{ab}	0.048
Pinus caribaea	Kodera Wakiso	46.81±0.43 45.26±0.23	0.009
Pinus patula	Kibiri Kodera	46.81±0.43 45.26±0.23	0.283

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Table 4.10 shows significant difference for *Cupressus lusitanica* ($p < 0.05$, SNK-test). *Cupressus lusitanica* in Kakamega, Ombo and Port Victoria shows significantly higher percentage carbon compared to Kodera. *Pinus caribaea*in Kodera and Wakiso showed significance difference in percentage carbon ($p < 0.05$, T-test). *Pinus patula* in Kibiri and Kodera did not show any significant difference in percentage carbon ($p >0.05$, T-test). These differences in percentage carbon in different region can be attributed to soil physiology (Michagan Forest Forever Teacher Guide, 1998).

4.5.3 Percentage Weight of Hydrogen.

Table 4.11 shows the percentage weight of hydrogen from six biomass samples. The table shows significance difference ($p < 0.05$, SNK-test). *Pinus caribaea, Calitris robusta,Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula* did not show any significance difference from one another. Sugarcane bagasse showed the lowest percentage of hydrogen.

Table 4.11: Mean percentage Weight of hydrogen.

Fuel type	% Hydrogen (Mean ± SE) n= 9
Pinus caribaea	5.44 ± 0.22^{b}
Calitris robusta	5.56 ± 0.17^{b}
Cupressus lusitanica	5.17 ± 0.34^{b}
Eucalyptus grandis	5.55 ± 0.13^{b}
Pinus patula	5.59 ± 0.18^{b}
Sugarcane bagasse	4.32 ± 0.13^{a}
p-value	0.003

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Hydrogen percentage of *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula* in this study were within the range as reported by Turn *et al*.(2005). However, Sugarcane bagasse showed lower percentage of hydrogen than those reported of 4.98 % (Turn *et al*.,2005). Cheremisnoff (1992) found that typical wood have 6 % hydrogen which is close to the result. Sugarcane bagasse showed lower percentage of hydrogen compared with Raveendran*et al*.(1995) who reported 5.8 %.The results obtained for sugarcane bagasse were slightly low compared to the one reported by Demirbas (2004) of 5.35%.

A comparison of percentage of hydrogen in selected regions in the LVB is shown in table 4.12 for *Cupressus lustanica, Pinus caribaea*and *Pinus patula.*

Table 4.12 Comparison of percentage Weight of Hydrogen in Selected Regions in the LVB for *Cupressus lusitanica, Pinus caribaea* and *Pinus patula*

Species	Region	% Hydrogen (Mean ± SE), n= 9	p-value
Cupressus lusitanica	Kakamega Kodera Ombo Port Victoria	4.28 ± 0.33^a 6.56 ± 0.29^b 5.73 ± 0.26^b 4.11 ± 0.49^a	0.003
Pinus caribaea	Kodera Wakiso	5.67±0.09 5.38±0.28	0.622
Pinus patula	Kibiri Kodera	5.18±0.31 5.80±0.18	0.111

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

Cupressus lusitanica showed significant difference in percentage hydrogen (p <0.05, SNK-test). *Cupressus lusitanica* in Kodera and Ombo showed significantly higher percentage hydrogen compared to Kakamega and Port Victoria (SNK-Test). *Pinus caribaea* showed no significant difference in percentage hydrogen in Kodera and Wakiso (p > 0.05, T-test). *Pinus patula,* also did not show significant different in percentage carbon in Kibiri and Kodera (p > 0.05, T-test). These differences in hydrogen are brought by soil physiology (Michagan Forest Forever Teacher Guide, 1998).

4.5.4 Percentage Weight of Oxygen

Table 4.13 shows a significance difference since (p < 0.05, SNK test). The percentage weight mean of *Pinus caribaea,Eucalyptus grandis* and sugarcane bagasse showed significantly higher level in relative to *Pinus patula.Calitris robusta* and *Cupressus lusitanica* since did not show significant difference from one another (SNK-test). The value obtained for sugarcane bagasse was higher compared Demirbas (2004) who found 39.55 % oxygen. Raveendran*et al.*(1995) reported 47.1 % oxygen which was close to the result. According to BTG (1987) showed that typical biomass material have oxygen percentage of 40 to 51 %. These values agree with the result.

Table 4.13: Mean percentage Weight of oxygen.

Fuel type	% Oxygen (Mean ± SE), n= 9
Pinus caribaea	48.36±0.35^{c}
Calitris robusta	46.46±0.27^{b}
Cupressus lusitanica	45.46±0.45^{b}
Eucalyptus grandis	48.39±0.37^{c}
Pinus patula	43.41±1.58^{a}
sugarcane bagasse	51.1±0.64^{c}
p-value	<0.0001

**Mean values followed by the same small letter(s) within the same column are not significantly different from one another (One-way ANOVA, SNK-test, α=0.05).*

4.6 Synthesis Gas Composition

Table 4.14 shows the predicted synthesis gas composition of CO, H_2 and CO_2 from six biomass fuels on dry weight basis using Gopal (2010) thermodynamic equilibrium model.

Table 4.14 Predicted synthesis gas

Biomass fuel	% CO_2 (mean ± SE), n= 9	% H_2 (mean ± SE), n= 9	% CO (mean ± SE), n= 9
Pinus caribaea	11.03±0.10	16.42±0.68	25.31±1.05
Calitris robusta	10.42±0.08	16.29±0.51	25.45±0.80
Cupressus lusitanica	9.79±0.11	15.92±1.06	26.66±1.78
Eucalyptus grandis	11.06±0.12	16.52±0.43	25.13±0.65
Pinus patula	10.30±0.51	15.43±0.91	24.39±1.43
sugarcane bagasse	13.02±0.26	15.04±0.54	24.47±0.88

Eucalyptus grandis showed 16.52±0.43 % H_2 and 25.13±0.65 % CO were slightly higher compared to Gopal (2010) who found 16.1 % H_2 and 24.0 % CO. Sugarcane bagasse showed 15.04±0.54 % H_2 and 24.47±0.88 % CO were almost similar with Gopal(2010) who found 15.4% H_2 and 23.4 % CO. TERI (2006) found that a typical biomass produces 18 to 22 % CO and 13 to 19 % H_2. This result were in agreement for % H_2 but were slightly lower for percent CO. The results obtained for *Pinus caribaea* and *Pinus patula* for H_2were in agreement with Pholoso (2009) who used pine wood for downdraft gasifier and found 15.5%

H_2. The results for CO in*Pinus caribaea* and *Pinus patula* were slightly lower compared withPholoso (2009) who reported 26.23%.

The table 4.14 shows the percentage hydrogen are very close to each other from the range of15.04 - 16.42 % which were in agreement with Chen (1987) model who found 15.8% hydrogen and also with Graham and Huffman (1981) who reported a range of 8.9 – 18.0 %. The percentage carbon monoxide for the six biomass fuel ranged from 24.39 - 26.66 % which was higher than Chen (1987) model who found 18.5 %. The percentage CO was in agreement with Graham and Huffman (1981) who reported a range of 11.9-26.3 %.

Banapurmath *et al*.(2009) reported 19% ± 3% CO and 18% ± 2% H_2 in a downdraft biomass gasifier which they used to produce approximately 17MWth electricity. These results were lower for CO but higher for H_2 compared to the result in table 4.14. Chawdhury and Mahkamov(2010) investigated the production of syngas from wood pellets and discovered the production of CO was between 19 to 22% and the production of H_2 was between 12 to 19 %. These results were close compared with the result in the study.

Sharma (2011) concluded that feedstocks which produced 15% of CO and 13% of H_2 were considered acceptable for gasification. Therefore *Pinus caribaea*, *Calitris robusta*, *Cupressus lustitanica*, *Eucalyptus grandis*, *Pinus patula* and sugarcane bagasse were considered acceptable for gasification.

CHAPTER FIVE
CONCLUSION AND RECOMMEDATIONS

5.1 CONCLUSION

Six biomass species *Pinus caribaea*, *Calitris robusta*, *Cupressus lustitanica*, *Eucalyptus grandis, Pinus patula* and sugarcane bagasse were selected. Proximate analysis, ultimate analysis and heat values were done on each of the components of the selected six biomass species. Estimation of synthesis gas was also done.

Fromthe ultimate analysis, nitrogen content ofthe six biomass fuels was less than 0.25±0.07 percentages, carbon content was in the range of 40.45to 48.88 which was high and hydrogen content was less than5.59±0.18percentages forthe six biomass sample. Fromthe proximate analysis, moisture content was highest in*Pinus caribaea*(56.69±0.32 %)and lowest in *Pinus patula* (25.74±1.54 %), energy content was high in *Pinus patula* (19.48±0.42 MJ/kg)and low in sugarcane bagasse (16.95±0.10 MJ/kg), ash content was high in sugarcane bagasse (2.94±0.14 %) and low in the rest of five biomass sample,volatile matter was high in sugarcane bagasse (82.71±0.19 %) and low in the rest of the biomass sample and finally fixed carbon was high in wood samples and low in sugarcane bagasse. Heating values was calculated and also predicted from the theoretical equations. The measured value of *Pinus caribaea*(18.61±0.12 MJ/kg) and the predicted value from Demirbas (1997), Tilman (1978) and Jenkins and Ebeling (1985) were as follows (18.56±0.52 MJ/kg, 18.56±0.52 MJ/kg and 18.93±0.12 MJ/kg) respectively. The predicted equations were almost similar with the measured values of the six biomass species.

The six biomass feedstock studied showed less than 5% ash content and less than 1 % nitrogen content which qualified them to be used as gasification fuels. The thermo-chemical data for the six biomass fuels(*Pinus caribaea*, *Calitris robusta*, *Cupressus lustitanica*, *Eucalyptus grandis*, *Pinus patula* and sugarcane bagasse) showed that they can be used for gasification because of low ash content and nitrogen content. Basing on the type of gasifier, all the six biomass can be used for downdraft gasifiers and also the sugarcane bagasse can be used for updraft gasifiers.

From study, *Pinus caribaea*, *Calitris robusta*, *Cupressus lustitanica*, *Eucalyptus grandis*, *Pinus patula* and sugarcane bagasse were considered acceptable for gasification since they estimated more than 15% CO and 13% H_2.

5.2 RECOMMENDATIONS

I. Similar type of study need to be extended for other biomass species available in the LVB.

II. Pilot plant study on laboratory scale may be carried out to generate electricity from biomass species.

III. Actual gasification can be carried out to compare the amount of synthesis gas generated from that of thermodynamic equilibrium model.

IV. The chemical characteristics of ash component can be carried out on selected gasifier fuels in the Lake Victoria basin.

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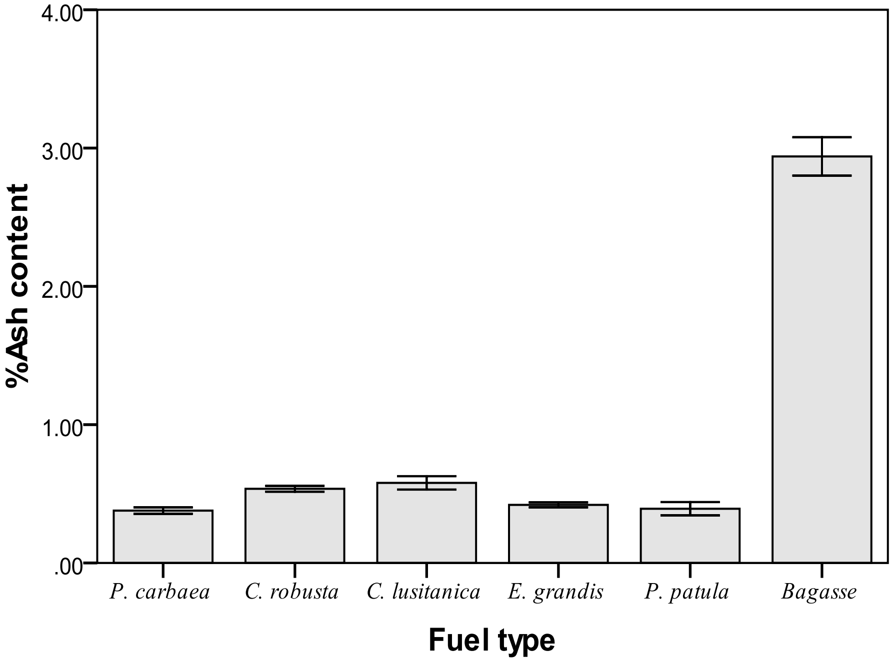
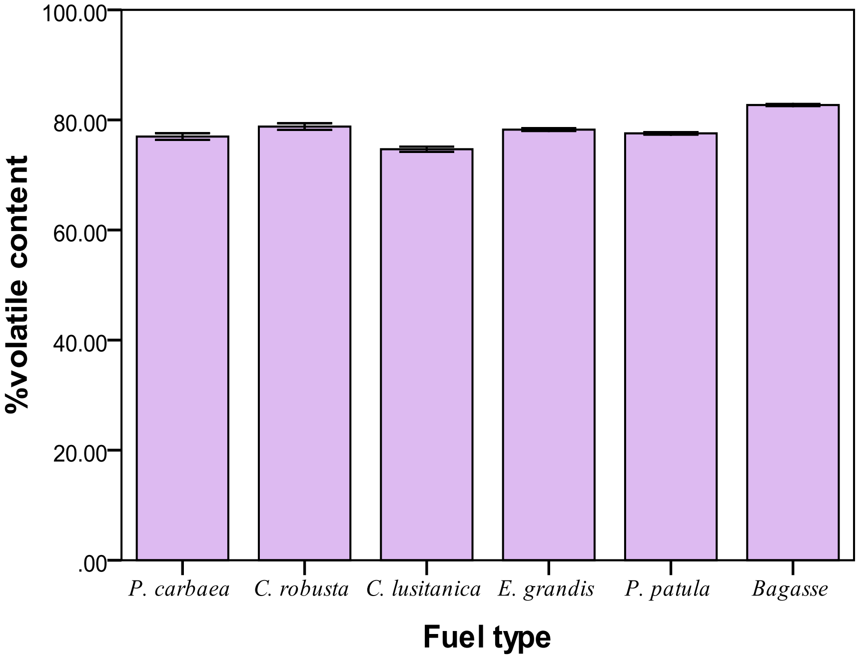
APPENDIXES

APPENDIX 1 Ash content of biomass fuels



APPENDIX II Volatile matter of biomass fuels



APPENDIX III Malava forest