



**PERFORMANCE EVALUATION OF DOWNDRAFT GASIFIER FOR SYNGAS
PRODUCTION USING RICE HUSK**

BY

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ZARIA, NIGERIA

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PRODUCTION USING RICE HUSK**

BY

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Dedication

This research is dedicated to my love ones whom in ALLAH'S will and destiny are no longer with us on earth , Include my late Dad, AlhajiSalihuAbdussalam, Late beloved Mum, HajiyaNi'imat Husain, Late Step Mum, HajiyaAsmau, Late close friend Zaid Muhammad and late Ali Abdussalam who bought the MSc form for me. Your memories will forever remain indelible in my mind, I pray to Allah in his infinite mercy to have mercy on your souls and bless you all with AljantulFirdaus. Crying.....

Declaration

I declare that the work in this dissertation entitled “performance evaluation of downdraft gasifier for syngas production using rice husk” has been carried out by me in the Department of Chemical Engineering, Ahmadu Bello University, Zaria. The information derived from the literature has been duly acknowledged in the text and list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other Institution.

JAMILU SALISU

Signature

Date

Certification

This dissertation entitled “performance evaluation of downdraft gasifier for syngas production using rice husk” by JAMILU SALISU meets the regulations governing the award of Master of Science in Chemical Engineering of the Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literacy presentation.

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Acknowledgement

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Abstract

Biomass gasification is a thermochemical process that converts biomass to a combination of gases known as syngas comprising mainly of CO, H₂ and CH₄ as a result of partial combustion with a gasifying agent. It is considered to be a promising clean energy option for reduction of greenhouse gas emissions and a way of utilizing agricultural wastes like rice husk. The syngas can be used not only to produce heat and power but in synthesis of liquid fuels and chemicals. This research comprises of rice husk characterization, mathematical model formulation to predict rice husk gasification theoretically and gasification of rice husk using both air and oxygen-enriched air as gasifying agents experimentally. Theoretical rice husk air gasification was done by inputting the composition of the characterized rice husk into set of mathematical equations derived based on thermodynamics, mass and energy balances using equilibrium approach and resulting equations were computed using MATLAB as a tool to predict syngas composition and calorific value between temperature of 500 and 1100 °C. Experimental rice husk gasification was conducted using a downdraft gasification system installed at National Research Institute for Chemical Technology, Zaria, Nigeria, comprising of a gasifier as reactor, cyclone, filter and air blower. The gasification was done with two different gasifying agents; air and oxygen-enriched air. For the air gasification, effect of 6.4, 3.0 and 0.7 L/min flow rates were studied while for the oxygen-enriched air gasification, 30 to 100% oxygen enrichment in air were examined. Temperature, syngas composition and calorific value were monitored during the experiment using online portable infrared syngas analyser (Gasboard 3100P series), digital thermometer (UT 350) and K-type (chromel-alumel) thermocouple. The results of the model indicated an optimum temperature at 800 °C with syngas composition of 18.72 CO%, 16.68% H₂, 13.05% CO₂, and 0.39% CH₄, and 4.47 MJ/m³ calorific value. The best experimental syngas composition was at 6.4 L/min air flow rate with composition of 10.83 CO%, 9.51% CO₂, 2.12% H₂ and 1.18 CH₄%, desired syngas composition of 14.13 % and equivalence ratio of 0.128, with an average temperature of 567°C and 2.53 MJ/Nm³ calorific value. Root mean square error value of 7.58 was calculated when the model developed was validated with the best results obtained from rice husk air gasification. For oxygen enriched- air rice husk gasification, the best point was considered at 50% oxygen enrichment in air having the highest CO to CO₂ ratio of 1.63 with equivalence ratio of 0.494, desired syngas of 24.34%, syngas composition of 19.8% CO, 12.16% CO₂, 2.26% H₂, 2.28% CH₄, and calorific value of 3.67 MJ/m³. Performance analysis shows that for air gasification the highest Carbon Conversion efficiency (CCE) and Cold Gas Efficiency (CGE) was achieved at the highest air flow rate (6.4L/min) as 21.27 and 12.55% respectively. While for oxygen-enriched air gasification, 50 % oxygen enrichment in air gave the best values of both CCE and CGE as 46.72 and 26.24%, respectively.

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List of Abbreviations

ER	Equivalence Ratio
DSC	Desired Syngas Components
HHV	Higher Heating Value
LHV	Lower Heating Value
CGE	Cold Gas Efficiency
CCE	Carbon Conversion Efficiency
M	Moisture content
VM	Volatile Matter
FC	Fixed Carbon
Wb	Wet Basis
M_{bm}	Molar Mass of Biomass
M_w	Molar Mass of Water
RMSE	Root Mean Square Error
CV	Calorific Value

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Access to cheap, reliable, and sustainable energy is a precursor for attaining and sustaining socio economic development. In fact it is fundamental requirement for poverty reduction. Currently about 90% of the world primary energy consumption is from fossil (petroleum, gas and coal), (Melgara*et al.*, 2009). However depleting of these fossil energy sources, the rate at which carbon dioxide (CO₂) is released into the atmosphere when they are burnt and increasing demand of the world energy due to population coupled with technological advancement are the current challenges. These challenges have served as motivation globally to develop alternative and renewable energy like biomass and solar that can help the present generation to meet their energy demand without jeopardizing the ability of the future generation to meet their energy demand.

Biomass is a non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms. They include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes. Biomass has high but variable moisture content and is made up of carbon, hydrogen, oxygen, nitrogen, sulphur and inorganic elements (Bhavanam and Sastry, 2011).The biomass is the only source of carbon-based renewable energy (Pandey*et al.*, 2013) and the most dominant renewable energy source used in the world today, comprising almost 80 per cent of the total supply. By 2050 energy from biomass could contribute 15%–50% of the world's primary energy (Beohara*et al.*, 2014). Presently about 25% of biomass is used by

developed countries, while 75% is used by developing countries to produce heat (Sahito, 2013).

Nigeria covers land area of 923,768 square km and the total land available for agriculture and vegetation is a measure of its biomass potential (Diyokeet *al.*, 2014). Nigeria has about 71.2 million hectares of available agricultural land, out of which about 36 million hectares of land are being currently utilized for agricultural production (Oladeji, 2011). Nigerian biomass energy resource is estimated to be 144 million tonnes/year (Diyokeetal., 2014). Sambo (2009) estimated Nigerian agricultural waste resources in million tonnes per annum as 11.2, with energy content of 147.7 GJ.

About 120 million tonnes of rice husks are generated annually in the world (Omatola and Onojah, 2012). In Nigeria about 2.0 million tonnes of rice is produced annually and 400 thousand tonnes of rice husk is generated out of it (Abalaka, 2012). These large quantities of biomass resources in Nigeria offer much potential for renewable energy and can play a significant role in meeting the country's energy demand if properly harnessed in modern and sustainable way.

Direct combustion has been the major way of utilization of biomass in Nigeria especially in rural areas. Fuel wood is used by over 60% of Nigerians living in the rural areas. Nigeria consumes over 50 million metric tonnes of fuel wood annually with alarming rate of deforestation. The rate of deforestation is about 350,000 hectares per year, which is equivalence to 3.6% of the present area of forests and woodlands, whereas reforestation is only at about 10% of the deforestation rate (Sambo, 2009).

The conversion of biomass to useful forms of energy can be achieved using a number of different biomass utilization technologies that can be separated into either

thermochemical processes or biochemical/biological processes as in fermentation and aerobic digestion (Caputo *et al.*, 2005).

The thermochemical conversions of biomass are combustion, pyrolysis and gasification. They constitute one of the promising routes among the renewable energy options of future energy because virtually all types of biomass can be used as feedstock even waste unlike their counterpart fermentation and aerobic digestion which are very specific in their biomass feedstock requirement. Biomass gasification has attracted the highest interest as it offers higher efficiencies compared to combustion and pyrolysis (Sheth and Babu, 2009). Gasification converts biomass into a combustible gas called producer gas or syngas consisting mainly of carbon monoxide, hydrogen and methane by partial oxidation. Gasification is also favoured among the other thermochemical conversion processes because it provides a syngas that can be used not only to produce heat and power but also in synthesis of liquid fuels and chemicals, such as biodiesel, methanol etc.

At present, the research on biomass gasification focuses on the optimization of the syngas production by means of a proper design, gasifier configuration, which includes fixed bed, fluidized bed, and entrained type gasifier. The right choice of the parameter values (type and amount of oxidant) and types of biomass also play a vital role in harnessing properly the energy in biomass using gasification technology.

1.2 Research Problem Statement

Currently the utilization of rice husk produced in Nigeria does not include producing energy from it. Inefficient way of utilizing biomass through combustion in Nigeria (wood fuel and charcoal) has contributed to desertification, deforestation and erosion in

the country. Biomass gasification technology as an efficient and sustainable way of utilizing biomass is not properly harness in Nigeria.

1.3 Justification of the Research

Gasification is an efficient way among other options to produce energy from biomass and is considered a very promising clean energy option for reduction of greenhouse gas emissions. Biomass gasification contribution to global warming is considered almost zero because carbon dioxide (CO₂) released when burned as a fuel in any form is naturally sequestered by photosynthesis (Basu, 2010). In addition, biomass fuels contain negligible amount of sulphur, so their contribution to acid rain is minimal (Luby, 2003). Gasification is part of clean development mechanism projects (CDM) which can earn Nigeria carbon credits and can be traded to countries who are trying to achieve their emission limits. Unlike other energy resource, using rice husk to produce energy is often a way to dispose of the biomass as waste that could otherwise create environmental risks. Energy from biomass gasification will reduce the dependency on the conventional source of energy from non-renewable fossil fuels. It will also serve as a major source of energy to rural areas where the conventional way of supplying energy could not be reached and this will help to reduce the rate of deforestation. Furthermore, it will create more value to growing of rice in Nigeria because economic value will be given to the rice husk generated as waste from rice production. This will translate to overall food security of the nation and new jobs will be created.

1.4 Aim and Objectives of the Research

The aim of the research was to study the performance of a downdraft gasifier using rice husk as feed stock.

The objectives of the research were:

- I. To determine the proximate and ultimate analysis of rice husk.
- II. To use equilibrium model to predict syngas composition using air gasifying agent.
- III. To study the effect of air and oxygen-enriched air as oxidants on the syngas composition in a gasification experiment.

1.5 The Scope of the Research

The research was limited to:

- I. Using only rich husk as biomass feedstock characterized via proximate and ultimate analyses
- II. Using downdraft gasifier installed at National Research Institute for Chemical Technology, Zaria.
- III. Utilizing air and oxygen enriched air as gasifying agents.
- IV. Monitoring of the gasification products (CO, CO₂, H₂, CH₄, O₂) and calorific value.
- V. The inside temperature of the gasification unit was monitored only at the combustion zone.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Background and Current Status of Gasification Technology

The salient features of town gas from coal were demonstrated to the British Royal Society in 1733, but the scientists of the time saw no use for it (Basu, 2010). Gasification was first used in 1792 when W. Murdoch, a Scottish engineer, used syngas from coal for domestic lighting purposes. In the 19th century, coal gasification became commercialized, illuminating several cities including New York City (Rivas, 2008).

The discovery of petroleum limits the use of gasification fuel. However during the World War II, shortage in petroleum supplies led to re-introduction of gasification and by 1945 the gas was being used to power trucks, buses and agricultural and industrial machines (Rajvanshi, 2014).

After the Yom Kippur War, On October 15, 1973, Arab members of the Organization of Petroleum Exporting Countries (OPEC) declared oil embargo to the United States and other western countries, which were at that time heavily reliant on oil from the Middle East. This shocked the western economy and gave a strong impetus to the development of alternative technologies like gasification (Basu, 2010).

Global warming and political instability in some oil-producing countries gave a fresh momentum to gasification during the current twenty first century. The threat of climate change stressed the need for moving away from carbon-rich fossil fuels. Gasification came out as a natural choice for conversion of renewable carbon-neutral biomass into gas (Basu, 2010).

2.2 Types of Biomass

Biomass may be divided into two broad groups: (a) Virgin biomass and (b) Waste. Primary or virgin biomass comes directly from plants or animals while waste or derived biomass comes from different biomass derived products. Table 2.1, shows these classification.

Table 2.1: Major Groups of Biomass and their sub Classification

Origin of biomass	Group of biomass	Sub classification of biomass
Virgin	Terrestrial biomass	Forest, Grass, Energy crops, Cultivated crops
Virgin	Aquatic biomass	Algae, Water plant
Waste	Municipal waste	Municipal solid waste, sewage
Waste	Agricultural solid waste	Livestock and manure, agriculture crop residue
Waste	Forestry residues	Bark, leaves, floor residues
Waste	Industrial waste	Black liquor, Demolition wood, waste oil or fat

Source: Bhavanam and Sastry (2011)

2.3 Components of Biomass

Cellulose, hemicellulose, lignin and extractives are found to be the major components of biomass. Cellulose and hemicellulose are formed by long chains of carbohydrates (such as glucose), whereas lignin is a polymeric phenolics. Lignin has a close

relationship with hemicellulose, as it acts as a glue fixing the bunches of cellulose chains and plant tissues together. Thus it gives mechanical strength to the plant. Lignin is rich in carbon and hydrogen, which are the main heat producing elements. Hence lignin has a higher heating value than carbohydrates (Vos, 2005). Table 2.2 shows the composition of biomass in terms of those components.

Table 2.2: Components of Different Biomass

Plant	Lignin (wt %)	Cellulose (wt %)	Hemicellulose (wt %)	Ash (wt %)
Subabul wood	24.7	39.8	24.0	0.9
Wheat straw	16.4	30.5	28.9	11.2
Baggasse	18.3	41.3	22.6	2.9
Corn cob	16.6	40.3	28.7	2.8
Groundnut shell	28.7	36.3	25.1	0.7
Millet husk	14.0	33.3	26.9	18.1
Rice husk	14.3	31.3	24.3	23.5

Source: Bhavanam and Sastry (2011)

2.4 Properties of Biomass

Properties of biomass are useful in order to evaluate their suitability as chemical feedstock in different processes. In evaluating gasification feedstocks, the following properties are generally useful: proximate (thermo-chemical behaviour) and ultimate (elemental composition) analysis and heating value (Stahl *et al.*, 2004). Composition of every biomass has carbon, hydrogen, and oxygen as major chemical elements. These element fractions can be quantified by ultimate analysis

Proximate analysis gives the composition of the biomass in terms of gross components such as moisture (M), volatile matter (VM), ash (ASH), and fixed carbon (FC)(Bhavanam and Sastry, 2011). Tables 2.3 and 2.4 show proximate analysis of some biomass on wet basis.

Table 2.3: Moisture Content of some Biomass

Biomass	Corn stalks	Wheat straw	Rice Husk	Dairy Cattle manure	Wood bark	Food waste
Moisture	40-60	8-20	7-10	88	30-60	70

(Wet basis)

Source: Basu (2010).

The ultimate analysis generally reports the elemental carbon (C), hydrogen (H), nitrogen (N), sulphur (S) composition and oxygen (O) vary from biomass to biomass. Elemental analysis is particularly important in evaluating the feedstock in terms heating value and of potential technical problems like reactor slagging and potential pollution problems. Ultimate analyses are reported using the $C_xH_yO_z$ formula where x, y, and z represents the elemental fractions of C, H, and O, respectively (Bhavanam and Sastry, 2011), Table 2.5 shows ultimate analysis of some biomass on dry basis.

A typical ultimate analysis is:

$$C + H + O + N + S + Ash = 100\% \text{ (Basu, 2010)} \quad (2.1)$$

The heating value of biomass is relatively low, especially on a volume basis, because its density is very low. The heating value may be reported on two bases. The Higher Heating Value HHV(gross heating value) represents the heat of combustion relative to

liquid water as the product. The Lower Heating Value (LHV) is based on gaseous water (Stahl *et al.*, 2004).

Higher Heating Value (HHV) is defined as the amount of heat released by the unit mass or volume of biomass (initially at 25 °C) once it is combusted and the products have returned to a temperature of 25 °C. It includes the latent heat of vaporization of water. HHV can be measured in a bomb calorimeter (Basu, 2010).

The Lower Heating Value (LHV) is defined as the amount of heat released by fully combusting a specified quantity less the heat of vaporization of the water in the combustion product (Basu, 2010).

The heating value is determined by the elemental composition, the ash content of the biomass and in particular on the fuel moisture content. On a dry and ash free basis, most biomass species have a heating value of about 19 MJ/kg (Arnavat, 2011).

Table 2.4: Proximate Analysis of some Biomass

Biomass		Bagasse	Coconut shell	Corn stalks	Groundnut shell	Rice husk	Subahul	Wheat straw
Proximate	VM	84.2	80.2	80.1	83.0	81.6	85.6	83.9
analysis	(wt %)							
	Ash	2.9	0.7	6.8	5.6	23.5	0.9	11.2
	(wt %)							
	Fixed	15.8	19.8	19.9	17.0	18.4	14.4	16.1
	carbon							
	(wt)							

Source: Bhavanam and Sastry (2011)

Table 2.5: Composition of Ultimate Analysis (Dry Basis) of Some Biomass

Biomass		Red wood	Sewage sludge	Rice straw	Rice husk	Sawdust	MSW	Animal waste
Ultimate	C (%)	53.5	29.2	39.2	38.5	47.2	47.6	42.7
Analysis	H (%)	5.9	3.8	5.1	5.7	6.5	6.0	5.5
	N (%)	0.1	4.1	0.6	0.5	0.0	1.2	2.4
	S (%)	0.0	0.7	0.1	0.0	0.0	0.3	0.3
	O (%)	40.3	19.9	35.8	39.8	45.4	32.9	31.3
	Ash (%)	0.2	42.1	19.2	15.5	1.0	12.0	17.8
	HHV(kJ/kg)	21,028	16,000	15,213	15,376	20,502	19,879	17,167

Source: Basu (2010).

2.5 Gasification Process

Gasification is a thermochemical process which breaks down biomass completely into a combustible gas, volatiles, chars, and ash in an enclosed reactor or gasifier. The process occurs when a controlled amount of oxidant (pure oxygen, air, steam) is reacted at high temperatures with available carbon in the fuel within a gasifier. This combustible gas is known as producer gas or syngas and consists of hydrogen (H₂), carbon monoxide (CO), methane (CH₄), carbon dioxide (CO₂), water vapour (H₂O), nitrogen (N₂), higher hydrocarbons and undesired products: particulate matter, dust, soot, inorganic pollutants and organic pollutants (tars) as well as ash (Reynolds *et al.*, 2013). The composition of any syngas strictly depends on the gasification conditions (reactor geometry, used gasification agents, operating conditions) and biomass properties.

Gasification is a two-step, endothermic process. In the first reaction, pyrolysis, the volatile components of the fuel is vaporized at temperatures below 600°C by a set of complex reactions. Included in the volatile vapours are hydrocarbon gases, hydrogen,

carbon monoxide, carbon dioxide, tar, and water vapour. As biomass fuels tend to have more volatile components (70-86% on a dry basis) than coal (30%), pyrolysis plays a larger role in biomass gasification than in coal gasification. Char (fixed carbon) and ash are the pyrolysis by-products, which are not vaporized. In the second step, the char is gasified through reactions with oxygen, steam, carbon monoxide and hydrogen. The heat needed for the endothermic gasification reactions is generated by combustion of part of the fuel, char, or gases, depending on the reactor technology (Boerrigter and Rauch, 2006).

2.5.1 Combustible gases

Product gas is generated by low-temperature gasification (below 1000°C) and contains CO, H₂, CH₄, C_xH_y aliphatic hydrocarbons, benzene, toluene, and tars. The syngas components (H₂ and CO) typically contain only ~50% of the energy in the gas, while the remainder is contained in CH₄ and higher (aromatic) hydrocarbons (Boerrigter and Rauch, 2006).

Biosyngas is produced by high-temperature (>1200°C) gasification or catalytic gasification. Under these conditions the biomass is completely converted into H₂ and CO (besides CO₂ and H₂O). Biosyngas is chemically similar to syngas derived from fossil sources and can replace its fossil equivalence in all applications. Biosyngas can also be made from product gas by heating (thermal cracking) or by catalytic reforming.

2.6 Different Processes Occurring in Gasification

In a gasifier, the carbonaceous material undergoes several different processes drying, pyrolysis, combustion, and gasification processes (Bhavanam and Sastry, 2011).

2.6.1 Drying

In this stage, the moisture content of the biomass is reduced and occurs at about 100-200°C with a reduction in the moisture content of the biomass of less than 5% (Arnavat, 2011). Resulting water vapour together with water vapour formed at combustion zone, partly lead to production of hydrogen and remaining is going with producer gas (Gunarathne, 2012).

2.6.2 Pyrolysis (Devolatilization)

Pyrolysis is the use of heat (pyro) to break down carbon based materials (lysis) without oxygen (Rivas, 2008). Devolatilization occurs at temperatures up to about 700 °C and releases light permanent gases (such as H₂, CO, CO₂, CH₄, H₂O, NH₃), tar which is the condensable hydrocarbon vapours and the remaining devolatilized solid waste residue known as char (Arena, 2012). About up to 70% weight loss for biomass occur in this stage and is dependent on the properties of the carbonaceous material, its also determines the structure and composition of the char, which will then undergo gasification reactions (Bhavanam and Sastry, 2011).

2.6.3 Combustion/Oxidation

The biomass is partially combusted producing heat. This heterogeneous chemical reaction requires no more than 25% of the oxygen needed for complete combustion (Rivas, 2008). An oxidation zone is formed at the level where air is introduced. Oxidation reactions are highly exothermic and result in a temperature rise which provide for auto-thermal gasification, the heat necessary for the endothermic reactions in the drying, pyrolysis and reduction zones. Apart from heat generation, another important function of the oxidation zone is to oxidize all condensable products from the pyrolysis zone. The process occurs as the volatile products and some of the char reacts with oxygen, the main reactions are (1) to (4) as shown in Table 2.6. The last of the

presented oxidation reactions also produces heat, which is beneficial to the gasification process, but it is not desired because it reduces the heating value of the syngas.

2.6.4 Gasification/Reduction

The sensible heat of the combustion gases and char is converted into the chemical energy of the producer gas (Chawdhurya and Mahkamovb, 2011). The reactions taking place are (5) to (9) shown in Table 2.6. The most important among these several gasification reactions are the water gas reaction (5), Boudouard reaction (6) and methanation reaction (7) (Arena, 2012).

In addition, the reversible gas phase water gas shift reaction reaches equilibrium very fast at the temperatures in a gasifier and its balance the concentrations of various components in the producer gas (Bhavanam and Sastry, 2011). All these gasification reactions, except the oxidation ones, are equilibrium reactions (Arena, 2012). However in practice, the equilibrium composition of the gas will only be reached in cases where the reaction rate and the time for reaction are sufficient. The reaction rate decreases with falling temperature, below 700°C, the water gas shift reaction proceeds so slowly that the syngas composition is said to be frozen when formed and the gaseous products do not further react with each other (Arnavat, 2011).

Table 2.6: Chemistry of Gasification Processes

Gasification stage	Reaction formula	Reaction number/Reaction type	Reaction heat (kJ/kmol)
Oxidation reactions	$C + 1/2 O_2 \rightarrow CO$	(1) Partial oxidation	+110,700
	$CO + 1/2 O_2 \rightarrow CO_2$	(2) CO oxidation	+283,000
	$C + O_2 \rightarrow CO_2$	(3) Total oxidation	+393,790
	$H_2 + 1/2 O_2 \rightarrow H_2O$	(4) Hydrogen oxidation	+241,820
Gasification /Reduction	$C + H_2O \rightarrow CO + H_2$	(5) Water-Gas	-131,400
	$C + CO_2 \rightarrow 2CO$	(6) Boudouard	-172,580
	$C + 2H_2 \rightarrow CH_4$	(7) Methanation	+74,900
	$CO + H_2O \rightarrow CO_2 + H_2$	(8) Water –Gas shift	+41,170
	$CH_4 + H_2O \rightarrow CO + 3H_2$	(9) Steam reforming	-206,300

Source: Luby and Mat (2003), Arnavat (2011), and Prakashand Sheeba (2014)

2.7 Gasifier Design

Gasifiers are mainly classified according to their design as fixed bed, fluidised bed and entrained flow bed. However, gasifiers can also be classified (Arnavat, 2011):

- I. According to gasification agent.
- II. According to heat for gasification (autothermal or allothermal) and
- III. According to pressure in the gasifier (atmospheric or pressurised)

2.7.1 Gasification in fixed bed reactors

They are sometimes called moving bed because the gasifying agent passes through a bed of solid fuel. If the gasifying agent is fed from the top of the reactor with the

biomass, it is term downdraft gasifier while if the gasifying agent is feed from the bottom moving counter currently with the biomass the gasifier is called updraft. These reactors are easy to construct, operate and suitable for small scale applications. They are widely available in developing countries but in general have limited scale-up properties.

2.7.1.1 Downdraft gasifier

In a downdraft gasifier, the feedstock and gasifying agent both move in the same direction. According to the design, the tarry pyrolysis products are passed through the glowing bed of fuel and tar is cracked in to gaseous products, so amount of tar is significantly lower than that in an updraft gasifier. Hence, this type is suitable for highly volatile fuels such as wood, for producing gas with low tar content and also suitable for power generation applications which require clean gas.

Drawbacks of the downdraft gasifier are the high amounts of ash and dust particles in the gas, limitation to operation with low density fuels due to flow problems and excessive pressure drop, slogging of ash and lower efficiency compared to updraft type due to lack of internal heat exchange. Downdraft gasifier demand a relatively strict requirements of the fuel like moisture content less than 25% (w.b.) and of uniform size in the range of 4-10 cm to realise regular flow (Arnavat, 2011). Syngas exits the reactor at high temperature (700°C) thus decreasing the reactor efficiency (Rivas, 2008). Configuration of a fixed bed downdraft gasifier is shown in Figure 2.1.

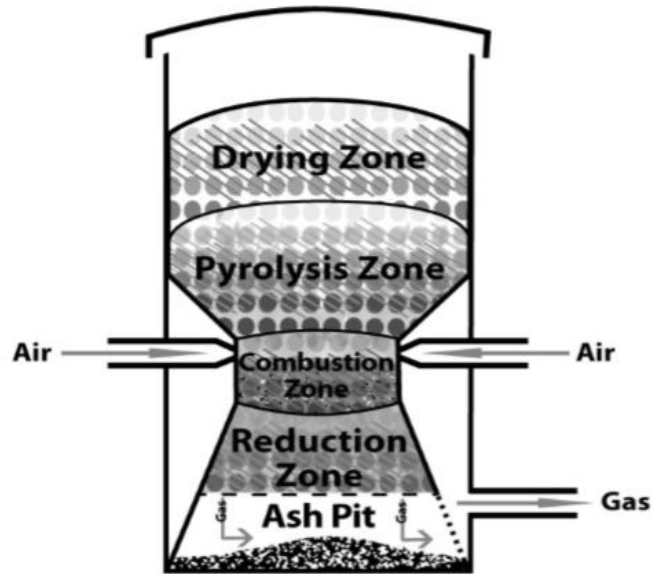


Figure 2.1: Fixed Bed Downdraft Gasifier

Source: Bhavanam and Sastry (2011)

In order to avoid cold spots in the oxidation zone, the temperature distribution should be even; the air inlet velocity and the gasifier geometry must be well chosen. Basically there are two methods to obtain an even temperature distribution at the oxidation zone (Different throat arrangement are shown Figure 2.2):

- I. One method to reduce the cross-sectional area at a certain height of the gasifier is known as "throat concept".
- II. To spread the air inlet nozzles over the circumference of the throat or using a central air inlet with a spraying device is another method.

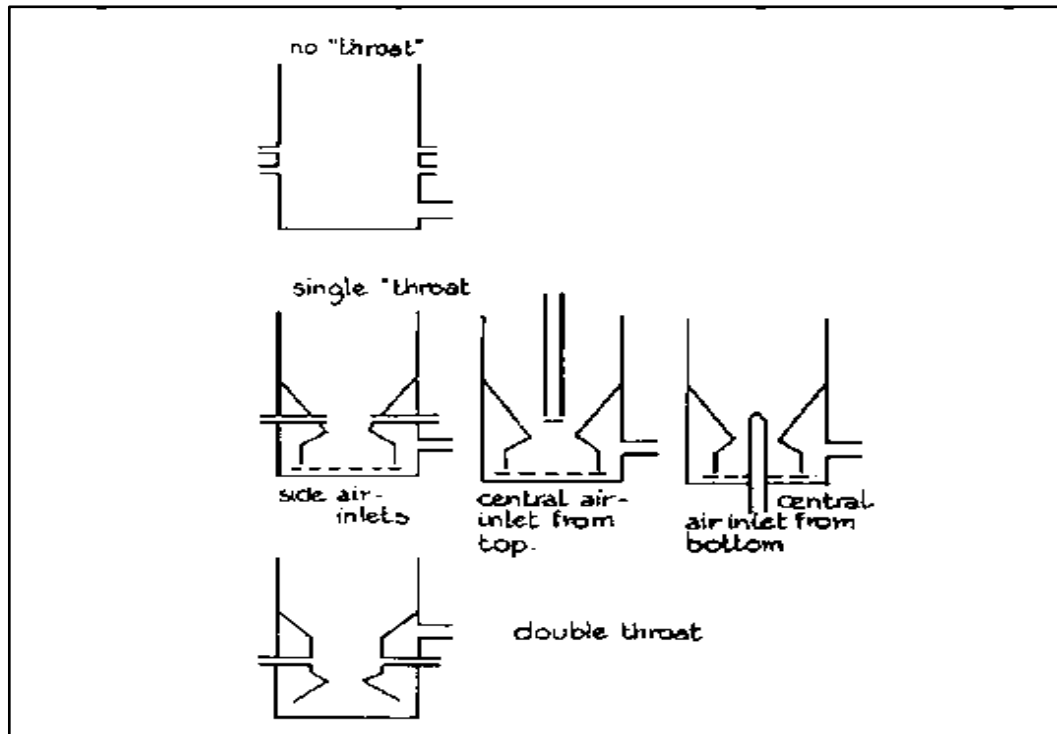


Figure 2.2: Different Throat Arrangement

Source: Gunarathne (2012)

The throat diameter has effect on the conversion efficiency of the gasifier and it has been reported that smaller throat diameters give higher conversions efficiency and vice versa. This is because the throats with larger diameters decrease the temperature due to divergent effect and hence the reaction rate. The efficiency also has been found to increase with the distance from the top reduction zone to the throat location and small throats need longer gasification. The throat angle also affects the gasifier conversion efficiency and small angles give higher conversion efficiencies and vice versa due to diverging effect of large angles. However, small angles require long reduction zones (Gunarathne, 2012).

Fixed bed downdraft gasifier can be classified into: Imbert gasifier (Throated or closed top gasifier) and the stratified gasifier (Throatless or open core gasifier).

2.7.1.1.1 *Imbert downdraft gasifier*

They are characterized by nozzle and hearth, below the air nozzle is the reduction zone consisting of a classical imbert hearth, it can be of “V” or flat sharp. The hearth constriction causes all gases to pass through the hot zone, the design of the hearth also allow retained ash to accumulate, improving the insulation which results in lower tar production. Figure 2.3 shows the configuration of an imbert downdraft gasifier.

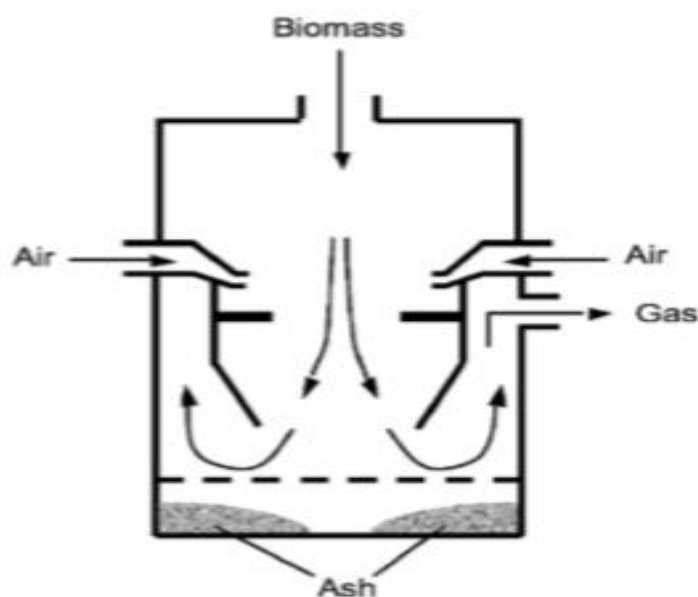


Figure 2.3: Imbert Downdraft Gasifier

Source: Basu (2010)

The imbert downdraft gasifier is generally used for gasification of biomass of uniform sizes and shapes as they flow smoothly through the constriction. They can handle only biomass fuel having ash and moisture content less than 5% and 20% respectively. The gasifier has lower overall efficiency since a high amount of heat content is carried over by the hot gas (Bhavanam and Sastry, 2011).

2.7.1.1.2 *Stratified downdraft gasifier*

The gasifier consists of a cylindrical vessel with a hearth at the bottom. During operation the air and biomass move downwards through the four zones in the reactor. The open top ensures uniform access of air and permits fuel to be fed easily and uniformly, which keeps the local temperatures in control (Bhavanam and Sastry, 2011). Upper layer is composed of unreacted biomass, in the second layer biomass reacts with air in flaming pyrolysis. The third layer, which is made up of char from the second layer, reduces the pyrolysis gases. The inert char, which constitutes the fourth layer, normally is too cool to cause further reactions.

The cylindrical nature of a stratified downdraft gasifier permits continuous flow, hence has no problem of bridging and channelling as countered in imbert downdraft gasifier. They are easy to construct, the open core make biomass to be fed easily into the reactor, the uniform passage of air and biomass down the gasifier also provide uniform temperature, the various strata are more accessible for measuring composition and temperatures. Stratified downdraft gasifier operates like a plug flow reactor and therefore can be easily scaled to a larger diameter. Figure 2.4 shows the configuration of a stratified downdraft gasifier.

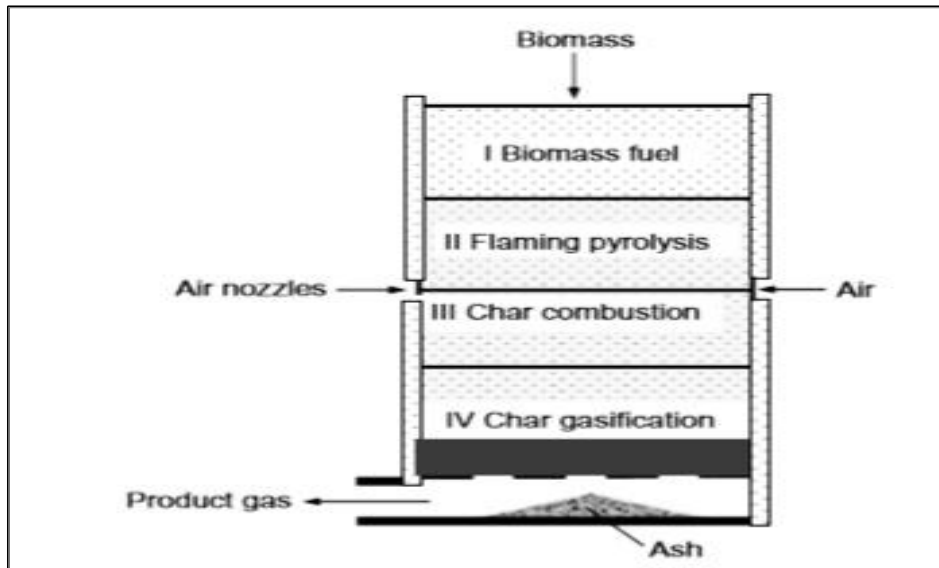


Figure 2.4: Stratified Downdraft Gasifier Design

Source: Basu (2010)

Disadvantages of stratified downdraft gasifier include higher dust generation because as char reacts in the gasification zone its break up into dust containing ash and some amount of original carbon. The dust may be carried away plugging the gasifier, this must be removed by shaking or stirring, which the stratified has no provision except in imbert downdraft gasifier.

2.7.1.2 *Updraft gasifier*

Also called counter-current gasifier, the biomass in this reactor is fed from the top and moves downward opposite to the air that flows from bottom to top. The heat transfer between the syngas and the biomass helps to cool the syngas before it exits (Rivas, 2008).

The major advantages of this type of gasifier are its simplicity, high charcoal burn-out and internal heat exchange leading to relatively low gas exit temperatures around (200-300°C) and high gasification efficiencies. Because of the internal heat exchange, the fuel is dried in the top of the gasifier and therefore fuels with high moisture content (up

to 60% w.b.) can be used. Furthermore, this type of gasifier can even process relatively small sized fuel particles and accepts some size variation in the fuel feedstock.

Major drawbacks are the high amounts of tar and pyrolysis products, since the syngas formed is not forced to pass through the hot high temperature zone that is pyrolysis products are not combusted. However this is of minor importance if the gas is used for direct heat applications, in which the tars are simply burnt. If the end-process requires tar-free syngas, as in case used for power production, extensive gas cleaning is required which can become a major investment. The configuration of an updraft gasifier is shown in Figure 2.5.

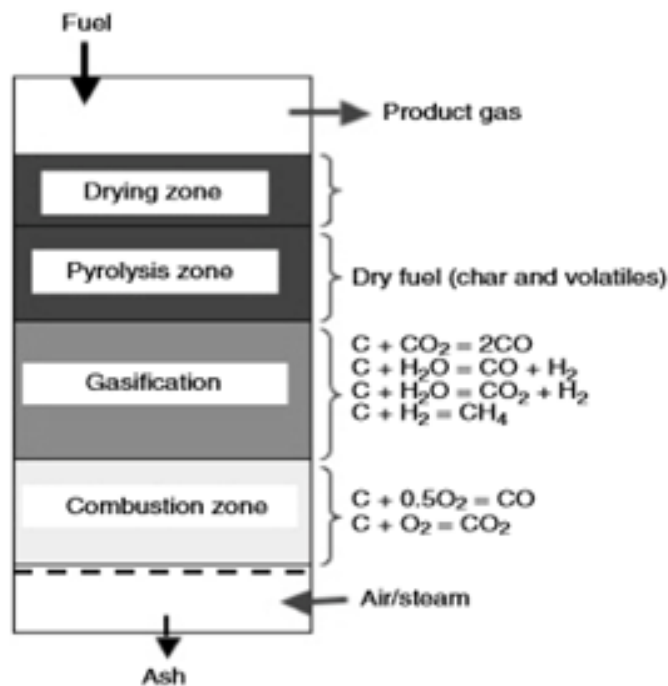


Figure 2.5: Updraft Gasifier

Source: Basu (2010)

2.7.1.3 Cross-flow gasifiers

Cross draft gasifiers are simple; air flows at high velocity through a nozzle located on a side of the gasifier opposite to where the producer gas leaves the reactor. Cross

draftgasifiers have very fast response times, Figure 2.6 shows the configuration of a cross draft gasifier. High temperature is reached in a small volume, thus low tar content can be achieved. Temperatures close to 1500° C around the combustion zone leading to syngas exits at high temperatures and also material problem such ash slagging (Rivas, 2008).

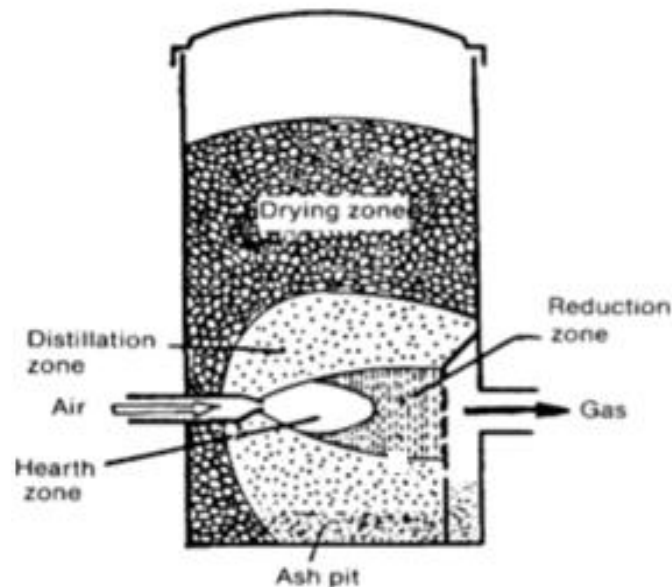


Figure 2.6: Cross Draft Gasifier

Source: Reed and Das (1988)

2.7.2 Fluidized bed gasifiers

In fluidized bed gasifiers, feedstock is fluidized with some bed material like sand/silica. The gasification medium flows in through the nozzle with a velocity enough to fluidize the particles above the grate and fluidises the bed material. The air passes upwards through the bed, and when the point where the pressure drop equals the gravity force of the particles, the particles become suspended and termed fluidised at the minimum fluidisation velocity. This is an important parameter in designing fluid bed reactors. Further increase of the air velocity causes the particles to move more and more vigorously resembling a boiling liquid (Arnavat, 2011). Above the bed itself the vessel

increases in diameter, lowering the gas velocity and causing particles to recirculate within the bed itself. The recirculation results in high heat and mass transfer between particle and gas stream, thereby increasing heating value of the output and higher efficiency.

The constant turbulence of the fuel and the bed material (back-mixing) ensures on the one hand that there is a very intensive contact between both, but on the other hand also prevents a similar partitioning into reaction areas as is the case with fixed-bed gasification (Lettner *et al.*, 2007). Due to the intense mixing the different zones (drying, pyrolysis, oxidation, reduction) cannot be distinguished like at fixed bed gasifiers; the temperature is uniform throughout the bed. Contrary to fixed bed gasifiers the air-biomass ratio can be changed, and as a result the bed temperature can be controlled, usually between 700 to 900°C (Arnavat, 2011).

Fluidised bed gasifiers are more suitable for large scale applications and for feed stocks with small particle size. Flexible to changes in fuel characteristics such as moisture and ash content. But the drawbacks are: high tar and dust content of the produced gas, high producer gas temperatures containing alkali metals in the vapour state, incomplete carbon burn out, and complex operation because of the need to control the supply of both air supply and solid fuel. There are mainly two kinds of fluidized bed gasifiers commercially used.

2.7.2.1 Circulating fluidized bed gasifier

In this type, the bed material removed from the combustion chamber must be precipitated out of the gas stream by a cyclone and then recirculates into the reaction chamber (Lettner *et al.*, 2007). This provides the significant advantages over the bubbling bed gasifier in terms of mass conversion efficiency and reduces particulate content in

the syngas output (Gautam, 2010). It has high conversion rate of tar and is suitable for large scale power generations. The carbon burn out in circulating fluidised bed gasifiers is considerably better than in bubbling fluidised beds (Arnavat, 2011). Figure 2.7 shows the configuration of a circulating fluidised bed gasifier.

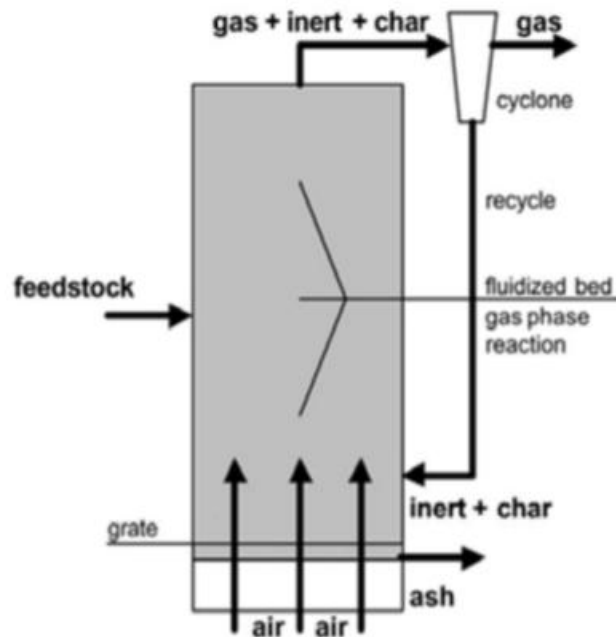


Figure 2.7: Circulating Fluidised Bed Gasifier

Source:Tasma and Panait (2012)

2.7.2.2 Bubbling fluidized bed gasifier

In this gasifier, the air is introduced through a grate at the bottom, and the feed is introduced above the grate into the moving bed of fine-grained material, where it is pyrolysed forming a char with gaseous compounds. This results in a gas with low tar content, since the high molecular weight compounds are cracked by the hot bed material (Sethuraman, 2010).Figure 2.8 shows the configuration of a bubbling bed fluidizing gasifier.

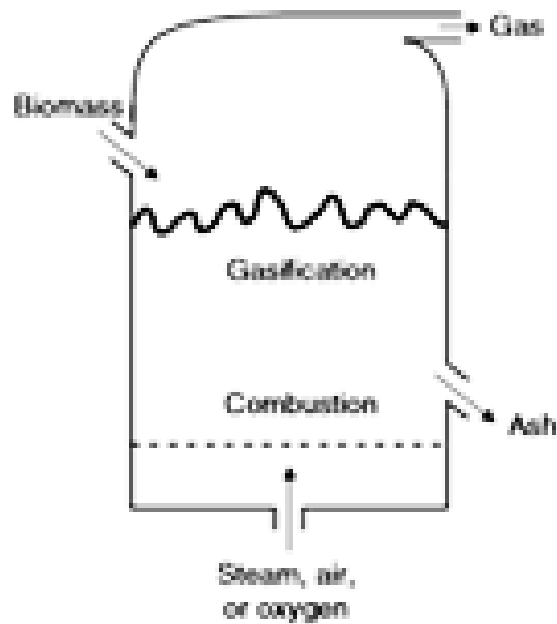


Figure 2.8: Bubbling Bed Fluidizing Gasifier

Source: Basu (2010)

2.7.3 Entrained flow gasifier

Fuel and gasifying agent are introduced at the top of the reactor vessel, and fuel is entrained by the gases in the vessel. The gasification reactions take place at very high reaction rate because of the high operating temperature (1200 – 1600 °C) and pressure (2 – 8 MPa), and after a few seconds (0.5 – 4.0 s) the product gas leaves the reactor vessel at the bottom together with the molten slag resulting from melting of ash (Qin, 2012).

Fine-grained ground solid biomass, whose grain size is smaller than 0.1 mm (10 µm) are generally the requirement of a entrained flow (gasifier Lettner*et al.*, 2007). Low methane and tar production but high oxygen requirements are other features of the EF-gasifier, which make it most suitable for H₂ -rich gas production (Muzee, 2012).

Entrained flow gasifiers have the ability to gasified practically any fuels, but fuel with lower moisture and ash content are favoured to reduce oxygen consumption but using biomass powder as fuel during entrained flow gasification may give an extra cost due to its low bulk density, which may need pre-treatment (Qin, 2012) . These types of gasifiers are the only attractive option for extremely large (> 1,000 MW thermal) bio-refinery systems (Muzee, 2012).Figure 2.9 shows the configuration of an entrained flow gasifier.

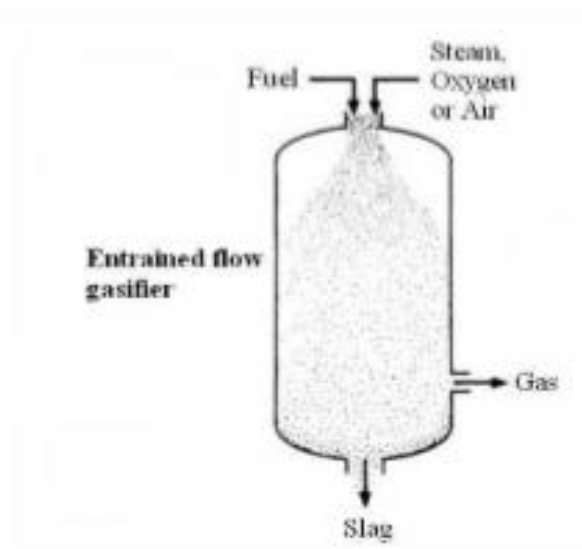


Figure 2.9: Entrained flow Gasifier

Source: Qin (2012)

2.7.4 Gasifiers suitable for biosyngas production

Biosyngas production: Biosyngas is produced by high-temperature (>1200°C) gasification. In principle, the (oxygen- blown) downdraft and the entrained flow gasification processes are suitable for this. However, downdraft fixed-bed gasifiers are limited in scale and require a well-defined fuel, making them not fuel-flexible. Therefore, the preferred process to produce biosyngas is entrained flow gasification (Boerrigter and Rauch, 2006).

2.8 Effect of Feedstock Properties on Gasifier Performance

2.8.1 Moisture

Fuel with moisture content above 30% makes ignition difficult and reduces the calorific value of the syngas due to the need to evaporate the additional moisture before combustion/gasification can occur. High moisture content reduces the temperature achieved in the oxidation zone, resulting in the incomplete cracking of the hydrocarbons released from the pyrolysis zone (Arnavat, 2011).

Moisture content in the biomass, during gasification, increases CO₂ concentration by the water-shift reaction which consumes CO and liberates H₂. While the equilibrium constant for water-shift reaction varies little over a wide range of temperatures, the direction tends to reverse at higher temperature due to the exothermic behaviour of the water-shift reaction. The decrease in temperature further forms more CO₂ since the water-shift reaction is improved at lower temperature. The overall effect is the reduction in calorific value of syngas because, the small increase in H₂ is not sufficient to compensate the loss of significant amount of CO with increase in moisture content. However, the negative effect of moisture content on the calorific value of syngas is lower at lower equivalence ratio (Gautam, 2010).

2.8.2 Volatile matter content

The amount of volatiles has an impact on the tar production levels in gasifiers. The gasifier must be designed to convert tars and the heavy hydrocarbons released during the pyrolysis stage of the gasification process.

2.8.3 Ash content

The mineral content in fuel that remains in oxidized form after complete combustion is usually called ash (Bhavanam and Sastry, 2011). High mineral matter can make

gasification impossible. The oxidation temperature is often above the melting point of the biomass ash, leading to clinkering/slagging problems and subsequent feed blockages. Clinker is a problem for ash contents above 5%. The use of moving grates has added the advantage of ability to operate with fuels having high ash content without slogging problem (Arnavat, 2011). Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response (Bhavanam and Sastry, 2011).

2.8.4 Bulk density

The bulk density refers to the weight of material per unit of volume. Fuels with high bulk density contain high energy content per unit volume and also require less space in fuel hopper. When the bulk density of fuel is low, it is difficult to flow under gravity and this result in low heating value of gas.

Fixed bed gasifiers have lower biomass feedstock size restrictions compared to fluidized bed gasifiers. Usually, feed size less than 51 mm and 6 mm is recommended for fixed bed and fluidized bed, respectively. The maximum particle size suggested for a conventional downdraft gasifier with throated design is one-eighth of the reactor throat diameter (Gautam, 2010). Larger particles can form bridges which prevent the feed moving down, while smaller particles tend to clog the available air voidage, leading to a high pressure drop and the subsequent shutdown of the gasifier. Decrease in particle size of the biomass feedstock in a downdraft gasifier reduces the heat loss to radiation and enhances the thermal conductivity in the oxidation; this therefore increases temperature in the oxidation and reduction. On the other hand, decrease in particle size increases pressure drop inside the gasifier. Increase in particle size of biomass decreases CO and CH₄ with increase in CO₂ and H₂. Also, the temperature gradient decreases thus increasing time taken for diffusion of heat. This will result in poor

temperature distribution which is also one of the reasons for the increase in CO₂ concentration with increase in particle size. Lower biomass size increases tar concentration because of high entrainment susceptibility during fluidization. This is because particles can be easily transported to the upper part of the reactor, leaving little time for tar cracking.

2.8.5 Elemental composition

Biomass elemental composition has a significant effect on syngas composition. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio. Pyrolysis gases increase when these ratios increase, especially with an increase in Hydrogen/Carbon ratio. A higher oxygen concentration in biomass needs lower equivalence ratio for gasification because of its inherent oxygen that will also be available for gasification.

To overcome limitations of above fuel properties, suitable pre-treatment of fuel is desired. Generally pre-treatment involves mechanical chipping for size reduction, screening to ensuring uniform size distribution and densification for low bulk density fuels.

2.9 Effect of Various Operating Parameters in Gasification Process

2.9.1 Gasification agent

Gasification agent is the means of supplying oxygen into the gasifier (Gunaratne, 2012). Selecting a gasification agent is important because it will depend on the reactor type. Different gasification agents can be used in the gasification processes; the most commonly used are air, oxygen, carbon dioxide, and steam (Rivas, 2008). In most biomass applications the gasifiers are operated with air as gasification medium affording a syngas diluted with nitrogen. For the more advanced applications, a

nitrogen-free syngas is required. A nitrogen-free syngas can be produced by oxygen-blown gasification or alternatively by indirect processes (Boerrigter and Rauch, 2006).

Air gasification is straight forward and very simple, requiring less capital and operating cost. However presence of inert nitrogen in air dilutes the gas and hence lowers the calorific value per unit volume of gas, this is because high amount of sensible energy is lost in heating the nitrogen from air (Gunarathne, 2012).

Oxygen gasification can be achieved by removing nitrogen from air prior to supplying to the gasifier (Gunarathne, 2012). The production of syngas using oxygen as a gasification agent is a way to generate nitrogen free syngas (Rivas, 2008). Steam gasification is the use of steam as a gasification agent which can increase H₂ content and the heating value of the producer gas; however, using steam in gasification is an endothermic process requiring a special heating supply design (Rivas, 2008). Air-steam mixtures, the addition of oxygen/air to the gasification medium composed of steam can generate the heat necessary for gasification reactions hence the gasifier can operate auto-thermally. The use of air-steam gasification can produce a higher H₂ yield compared with air gasification alone (Rivas, 2008). The use of CO₂ in gasification is promising because it is one of the gasification products. CO₂ enhances tar reduction reaction in the presence of catalysts as well as increases H₂ and CO composition (Rivas, 2008). CO₂ are mostly used together with other gasifying agents, Rafidah *et al.* (2011) gasified oil palm trunk with gasifying agent mixture of steam - CO₂, and resulted with syngas composition of 3.75% N₂, 30.10% CO, 9.91% H₂, 51.69% CO₂ and 3.28% CH₄. Table 2.7 shows yield of syngas with some gasifying agents.

Table 2.7: Composition of Syngas Gas with Different Gasifying Agent

Gasifying agent	T(⁰ C)	Gas composition (dry basis)		Tar (g/kg)	Gas rate (Nm ³ /kg)	Calorific value LHV (MJ/Nm ³)
		H ₂ (%)	CO (%)			
Air	780-830	5.0-16.3	9.9-22.4	3.7-61.9	1.25-2.45	3.7-8.4
O ₂ -Steam	785-830	13.8-31.7	42.5-52.0	2.2-4.6	0.86-1.14	10.3-13.5
Steam	750-780	38-56	17-32	60-95	1.3-1.6	12.2-13.8

Source: Rivas (2008)

2.9.2 Equivalence ratio

Equivalence ratio (ER) is the ratio of actual air fuel ratio to the stoichiometric air fuel ratio which provides the basis for evaluating the amount of air supplied for the gasification with respect to the amount of air required for the complete combustion or stoichiometric oxidation of the feedstock. ER is the most influential parameter in any gasification process and often has significant impact on syngas composition. Increase in ER increases the temperature inside the gasifier, which is probably due to occurring exothermic reaction because of existence of more oxygen in the system. The theoretical gasification occurs between ER values of 0.19-0.43 and theoretical optimum point for gasification is near 0.25 ER (Gunarathne, 2012). Also high ER value results in a lower concentration of H₂ and CO as well as in a higher CO₂ content in the syngas. Thus, a higher ER decreases the heating value of the syngas. Increasing the ER also has a beneficial effect on reducing tar formation given the greater availability of oxygen to react with volatiles. This phenomenon is more significant at higher temperatures. On the other hand, an increase in the steam/biomass ratio is expected to produce a higher hydrogen fraction as a result of the water gas shift reaction. In addition, excess steam often drives the cracking of higher hydrocarbons and reforming reactions. Figure

2.10 shows the effect of equivalence ratio on temperatures of gasification reactions and syngas composition.

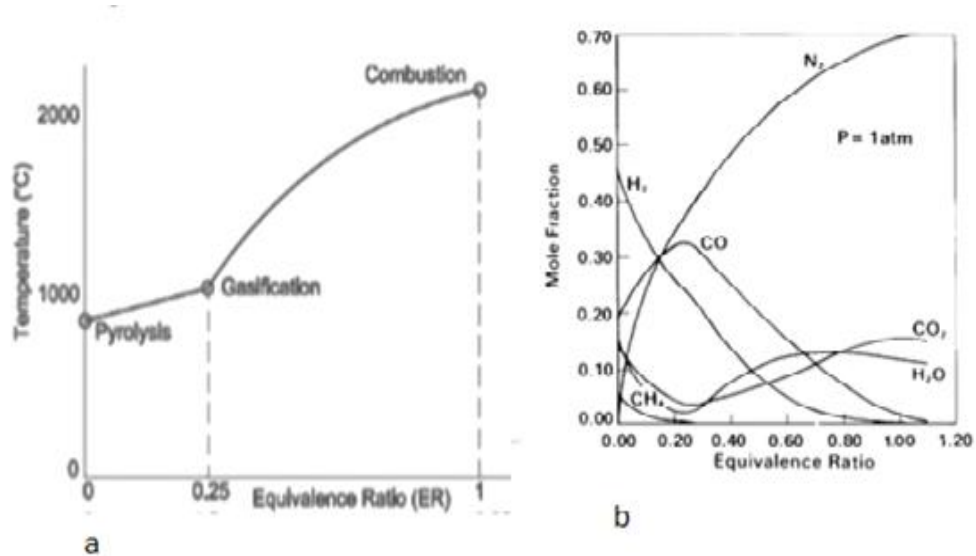


Figure 2.10: (a) Effect of Equivalence Ratio on Temperature of Pyrolysis, Gasification and Combustion (b) Composition of Syngas with Respect to Equivalence Ratio

Source: (a) Bhavanam and Sastry (2011), (b) Handbook of biomass Downdraft Gasifier Engine Systems (1988).

2.9.3 Operating temperature

The effect of temperature has significant impact in overall gasification process. Increase in temperature reduces the tar content as well as decreases char inside the gasifier. Higher temperature cannot be achieved without increasing equivalence ratio which in turn, reduces quality of the syngas. Preventing heat losses from the gasifier by proper insulation can reduce air need to maintain the sustainable gasification temperature (Gautam, 2010).

For auto thermal (directly heated) gasifiers, the reactor temperature profile is a state variable of the process, the system answer to different parameters, such as the equivalence ratio, residence time, insulation, moisture content of biomass etc. Where

external supply of heat is provided to the gasifier that is allo-thermal (indirectly heated) the temperature can be adjusted (Arena, 2012).

Syngas rich in H₂ and CO is produced at high reaction temperatures (800-850°C) and most gasifiers operate optimally between this range. This phenomenon can be due to the water shift reaction at high temperatures and tar cracking reactions at this temperature (Rivas,2012).

2.9.4 Operating pressure

Gasifiers can be operated at either atmospheric or elevated pressures. High-pressure gasification reduce the need for further compression when the gasification products are intended for subsequent use in Fischer-Tropsch process or other chemical synthesis which requires high pressure. Pressure drop across the gasifier increases with smaller particle size due to increased porosity. cIncrease in pressure in a fluidized bed increases turbulence and thus increase in gas-particle interaction is observed (Gautam, 2010).

2.9.5 Residence time

Residence time of gases and waste inside the reactor, which is largely defined by reactor type and design, and for a fixed gasifier design can be varied to a limited extent: for instance, in a fluidized bed, by varying the superficial gas velocity and, in a moving grate, by increasing the velocity of the grate elements (Arena, 2012).

2.10 Gas Cooling

Gasifier normally discharge producer gas at (500-800°C) and is cooled down if dry particle filtration with ceramic filters or fabric filters gas cooling is to used. For gas utilization in internal combustion engine a temperature below 40°C is required to attain a volumetric efficiency (Lettner *et al.*, 2007). Most coolers are gas to air heat exchangers where the cooling is done by free convection of air on the outside surface of

heat exchanger. Since the gas also contains moisture and tar, some heat exchangers provide partial scrubbing to eliminate tar, water vapour together with dust condensation(Rajvanshi, 2014). Heat exchanger can also be used to preheat incoming air while cooling down the producer gas (Gunarathne, 2012).

2.11 Gas Clean-Up Technologies

As syngas leaves the gasifier, it contains several types of contaminants that are harmful to downstream equipment, ash handling, and emissions. The degree of gas clean-up must be appropriately matched to its intended downstream application. Despite the type of application in which the produced gas is meant for, it must meet the requirement of the specific application. It would be preferable to design gasifiers that minimize the contaminants but since these contaminants are inevitable, therefore additional gas cleaning must be considered. Depending on the feedstock, the type of gasifier used and other factors the composition of the produced gas will vary. For a direct combustion system the raw gas may be used with little clean-up but for use in a gas turbine and other application extensive clean-up may be needed (Arnavat, 2011).The primary contaminants in syngas are tars,particles,alkali compounds, and ammonia.Table 2.8 shows some of the contaminants in a gasification system.

Table 2.8: Contaminants in a Gasification System

Contaminant	Description	Treatment
Tar	tar are complex hydrocarbons persist as condensable vapours	Wet scrubbers, electrostatic precipitators, barrier filters, catalyst
Particles	Particles are very small, solid materials that typically include ash and unconverted biomass	Cyclone separator, fabric filters, electrostatic precipitators and wet scrubbers
Alkali compounds	Potassium, alkali salts, and condensed alkali vapour are part of chemical composition of biomass	First, cool syngas below 1,200°F causing alkali vapour to condensate and the use cyclone separators, fine fabric filters, Wet scrubbers and electrostatic precipitators
Ammonia	Ammonia is formed from nitrogen based biomass	Catalyst, hydrocarbon reforming, or wet scrubbers

Source : EPA (2007)

Particulates are unwanted in the syngas since they can cause erosion on downstream equipment which leads to a shortened time of operation. The gas cleaning can be either dry or wet. Figure 2.11 shows performance of some syngas cleaning equipments.

Dry gas cleaning can be divided into hot gas cleaning with heat-resisting filters (at raw gas temperatures typically above 500°C and before gas cooling) and into dry gas cleaning in fabric filters (typically below 200°C after gas cooling). Filter elements for

hot gas cleaning typically consist of porous ceramic or sinter metallic materials. Hot gas cleaning is primarily interesting for gas utilization at high temperatures such as gas turbines and fuel cells. Possible cleaning steps in the hot gas cleaning process can be of the following (Lettner *et al.*, 2007):

- I. Cyclone as particulate removal prior to gas cooling
- II. Hot gas filter as particulate removal prior to gas cooling
- III. Filter system (bag, sand bed, active coke bed filters) as particulate removal after gas cooling.

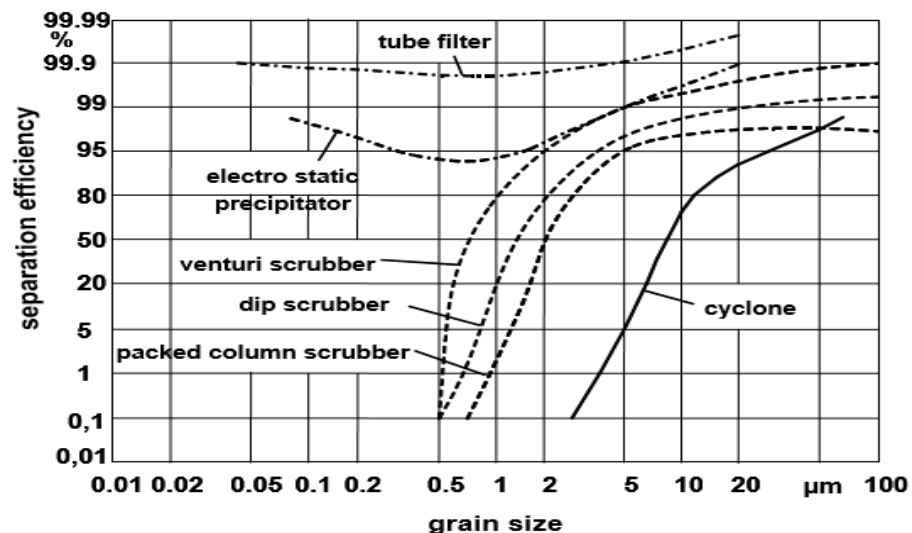


Figure 2.11: Performance of Different Clean Up Component

Source: Gasification Guide – Technology Description (2007)

Wet gas cleaning is the purification of the producer gas by means of liquid scrubbing agents in a suitable scrubber system. The cleaning effect is brought about by the adherence of the contaminants to and the dissolving of the contaminants by washing agents. This kind of gas cleaning additionally fulfils the function of gas cooling because of the heat exchange between the producer gas and the washing agent due to the

intensive contact and the heat removal through heat extraction via suitable heat exchangers.

Biomass can contain large amounts of alkali compounds. This is problematic since some of these contaminants can vaporize at temperatures of about 700°C. Therefore these alkali vapours cannot be separated by filtration. When the gas temperature then is lowered the vapours will start to condensate and form particles which finally deposit on cooler surfaces of the downstream equipment (Arnavat, 2011).

Ammonia is the primary contamination originating from nitrogen in the biomass. It is formed from protein and other nitrogen-containing components. In pressurized gasification there is a higher ammonia production because of the equilibrium considerations. Ammonia in the syngas is unwanted due to the formation of NO_x when the syngas is burned (Arnavat, 2011).

If the biomass contains sulphur it can be converted to hydrogen sulphide or sulphur oxides when gasified. However, most of the different biomass fuels contain very low shares of sulphur (<0.1% in wood) although refused derived fuels can contain higher levels. So, with most biomass, the concentrations of hydrogen sulphide and sulphur oxides are below clean-up requirements for most applications (Arnavat, 2011).

When a carbonaceous material is heated the molecular bonds that hold the material structure together fracture resulting in the release of long chain molecules during the devolatilization process. The smallest molecules are light gases (e.g. hydrogen, carbon monoxide and methane). The larger molecules are referred to as “tars”, which are long chain hydrocarbon molecules that resemble the original fuel material. Operationally, “tar” species in gasification syngas are important because they can condense in significant quantities at relatively high temperature (<700°F). Formally, gasifier tars are

defined as all organic products with a boiling temperature above that of benzene. The accumulation of condensed “tars” on components in the gasification system can lead to clogging, corrosion, slagging and catalyst deactivation (Sweeney, 2012). Also at temperatures above 400°C the tars can undergo reactions forming solid char and coke that can plug the equipment. Besides the operational problems, tar also means that the gasification efficiency is reduced. However the presence of tar can be accepted if the syngas is to be used in equipment such as burner (Arnavat, 2011).

Tars formed during the gasification process at temperatures less than 800°C can be handled using standard safety practices, while tars formed at temperatures above 800°C are much more hazardous to human health (Arnavat, 2011).

There are two tar cracking methods mainly: primary and secondary methods (Rivas, 2008). The primary methods focused on preventing tar formation before syngas is produced. The gasification’s operational parameters are controlled to reduce the amount of tar generated during the gasification process as well as in a bed catalyst procedure. These methods also consider the gasifier design (Rivas, 2008).

Gasifier modification for tar reduction can be divided into : the addition of air injection, recirculation of pyrolysis gas, modification of outlet gas, modification of combustion zone position, separation process of pyrolysis and reduction at different chamber (Surjosatyo *et al.*, 2010).

This kind of design include:

- I. Two stage gasifier: This gasifier is an updraft gasifier that has one gas outlet above the drying zone and another one just at the top of the gasification zone. The temperatures attained in these two zones are considerably lower than

the conventional updraft gasifier. Therefore, the incoming fuel is heated and the tar is evolved in a much slower manner.

- II. Two stage throatless downdraft gasifier: This gasifier is different from the conventional type by adding secondary air inlet at the middle part of reactor. By applying two air intakes, the temperature in the first stage would be decreased. Adding secondary air injection would help to combust the producer gas, it is aimed at increasing the temperature at the reduction zone and then cause tar reduction by cracking (Surjosatyo *et al.*, 2010).

Secondary tar removal methods can be described as methods that remove tar from the syngas after gasification reactions (Rivas, 2008). These methods are categorized as physical methods and tar cracking methods (thermal or catalytic). While primary methods are generally less effective than secondary methods, secondary methods are generally more expensive, and can shift the problem of tar in synthesis gas to disposal of the material used to remove the tars (Sweeney, 2012).

Physical methods include the use of wet scrubbers, electrostatic precipitators, cyclones, or barrier filters. The most effective way to physically remove tars is to use wet scrubbers and electrostatic precipitators.

Tar cracking methods include catalytic and thermal tar destruction. In these processes, tars thermally decompose to form additional syngas and sometimes char. Tar destruction can be accomplished with thermal energy alone at above about 1200 °C or with catalysts at moderate temperatures of 750-900 °C (Arnavat, 2011), catalysts used for gasification include naturally occurring catalysts such as dolomite and olivine, Alkali metals catalyst, alumina, metal oxide, and char.

Rivas (2008) reported that up to 99% of tar was converted into lower gases by using Ni/V-Al₂O₃ and Ni-char catalyst. Syngas composition without catalyst ranged between 19- 20% H₂ and 14-16% CO. with the use of catalyst, syngas composition increased to 51.90% H₂, 18.36% CO (Ni-char) and 51.78% H₂, 21.10% CO (Ni/V-Al₂O₃), while tar decreased down to 0.01 g/m³ in both cases.

In application, problems are seen mainly with catalytic converter service lifetimes due to catalyst poisons present in the producer gas (sulphur compounds, heavy metals, etc.). In general, de-dusting has to be carried out prior to catalytic conversion (Lettner *et al.*, 2007).

2.12 Gas Utilization

It is important to understand that gases from biomass gasification differ in their applications depending on gas specifications and the composition of the gasification gas is very dependent on the type of gasification process, gasification agent and the gasification temperature. The utilization can be categorised based on the two types of gases from biomass gasification that is product gas and biosyngas as shown in Figure 2.21

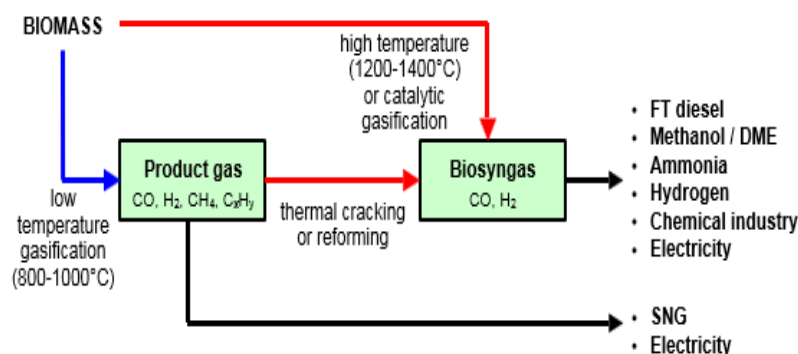


Figure 2.12: Utilization of Gases from Gasification
Source: Boerrigter and Rauch (2006).

2.12.1 Product gas application

The main application at present of product gas from gasification can be divided into three categories:

- I. Direct thermal application.
- II. Power generation.
- III. Synthetic natural gas (SNG) production.

More advanced applications are not first choice, as the syngas components H_2 and CO represent approximately 50% of the energetic value of a product gas. The only exception is the production of synthetic natural gas (SNG), in the presence of CH_4 is beneficial to achieve high overall yields (Boerrigter and Rauch, 2006).

2.12.1.1 *Direct thermal application*

Direct heat systems are those in which the producer gas is burnt directly in furnace or boiler. Due to direct burning of gas, a thermal application does not demand cleaning of gas and hence, can be operated with high tar and dust content. Efficiency of thermal application of gasification is in the range of 90% (Gunarathne, 2012).

Because of low energy content of producer gas ($\sim 5 \text{ MJ/m}^3$) which is about 10-15% that of natural gas, special burners are needed. Since the adiabatic flame temperature of producer gas is about 1400°C . The highest temperature applications can be around $1000\text{-}1200^\circ\text{C}$ (Rajvanshi, 2014).

2.12.1.2 *Power generation*

The main technologies able to use producer gas to generate power and/or heat are (Arnavat, 2011):

- I. Internal combustion engines (ICE)

- II. Steam turbines
- III. Gas turbines
- IV. Externally fired gas turbines (EFGT)
- V. Combined cycle systems (IGCC)
- VI. Fuel cells
- VII. Stirling engines

2.12.1.3 *Synthetic natural gas (SNG) production*

SNG production focuses mainly on gasification processes that yield product gases with high methane content. SNG is produced by methanation that is upgrading the producer gas to biomethane that can be injected into the existing natural gas grid replacing natural gas. Methanation is the catalytic reaction of carbon monoxide and/or carbon dioxide with hydrogen, forming methane and water. Consecutive and side reactions (shift conversion, Boudouard equilibrium, and hydrogenation of carbon) make the calculation of equilibrium conditions very complex. The methanation reactions of both carbon monoxide and carbon dioxide are highly exothermic under impact of a nickel based catalyst at a temperature of approximately 250 – 450 °C. Such high heat releases strongly affect the process design of the methanation plant since it is necessary to prevent excessively high temperatures in order to avoid catalyst deactivation and carbon deposition. The highly exothermic reaction generally creates a problem for the design of methane synthesis plants: either the temperature increase must be limited by recycling of reacted gas or steam dilution, or special techniques such as isothermal reactors or fluidised beds, each with indirect cooling by evaporating water, must be used (Boerrigter and Rauch, 2006; Allegue and Hinge, 2012).

2.12.2 Biosyngas

2.12.2.1 Power generation

Biosyngas is a combustible gas and can be used for the generation of electricity in all prime movers from steam cycles, to gas engines, turbines (combined cycle), as well as fuel cells. Based on energetic considerations, however, this is not an attractive utilisation of the syngas. It is more sensible to use product gas instead of biosyngas for power production. This originates in the lower net energetic efficiency of biosyngas compared to product gas production due to the higher gasification temperature and electricity consumption for oxygen production (Boerrigter and Rauch, 2006).

2.12.2.1 Transportation fuels

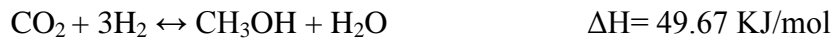
In the future, biosyngas will become increasingly important for the production of ultra-clean fuels from GTL processes, with the main examples being Fischer-Tropsch diesel and methanol/DME (Boerrigter and Rauch, 2006).

Fischer-Tropsch processes can be used to produce either a light synthetic crude oil (syncrude) and light olefins or heavy waxy hydrocarbons. The syncrude can be refined to high quality, if hydrocracked and/or isomerised, to produce excellent diesel fuel, lube oils, and naphtha, which is an ideal feedstock for cracking to olefins (Boerrigter and Rauch, 2006).

Methanol can be produced by means of the catalytic reaction of carbon monoxide and some carbon dioxide with hydrogen.

Methanol can be produced by means of the catalytic reaction of carbon monoxide and some carbon dioxide with hydrogen. Both reactions are exothermic and proceed with volume contraction; a low temperature and high pressure consequently favours them.

The chemistry of methanol synthesis is as follows (Allegue and Hinge, 2012):



Side reactions, also strongly exothermic, can lead to formation of by-products such as methane, higher alcohols, or dimethyl ether (DME) (Boerrigter and Rauch, 2006).

2.12.2.3 *Chemical synthesis*

Syngas can also be used in production of useful chemicals such as ammonia for fertiliser production, hydrogen in refineries, hydroformylation of olefins, olefins and aromatics, mixed alcohols.

2.13 **Gasifier Performance**

2.13.1 **Gas composition**

During gasification system, the syngas composition measured as volume percent of CO, CO₂, H₂, H₂O, CH₄, higher hydrocarbon(C₂+) and N₂, determine to a greater extent the performance of the gasifier, Table 2.9 shows composition of syngas from various biomass.

Table 2.9: Composition of Syngas from Various Biomass

Biomass	Gasification method	Volume percentage					Calorific value (MJ/m ³)
		CO	H ₂	CH ₄	CO ₂	N ₂	
Wood	Downdraft	17-22	16-20	2-3	10-15	55-60	4.60-5.86
Wheat straw	Downdraft	14-17	17-19	-	11-14	-	4.50
Pressed sugarcane	Downdraft	15-18	15-18	-	12-14	-	5.30
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29
Rice hulls	Downdraft	16.1	9.6	0.95	-	-	3.25
Charcoal	Updraft	30	19.7	-	3.6	46	5.98

Source: Rajvanshi (2014)

2.13.2 Gas energy content

The energy content can be calculated from the gas composition, or it can also be measured calorimetrically. The Gas must have energy content greater than 4 MJ/Nm³ for most application (Reed and Das, 1988).

2.13.3 Quantity of tar

The quantity of tar in raw gas determines whether the gas can be cleaned. Above 5000 mg/Nm³ tars, the gas is difficult to clean up and suitable only for direct combustion. Gas clean-up equipment should be able to reduce the tar level to below 10 mg/Nm³ (Reed and Das, 1988).

2.13.4 Quantity and size of particulates

The nature and quantity of char-ash and soot entrained in the gas stream can help in the design of filters. Particles larger than 10µm must be removed to a level below 10 mg/Nm³ for engine application (Reed and Das, 1988). Figure 2.13 shows particulate and tar in various biomass gasifiers.

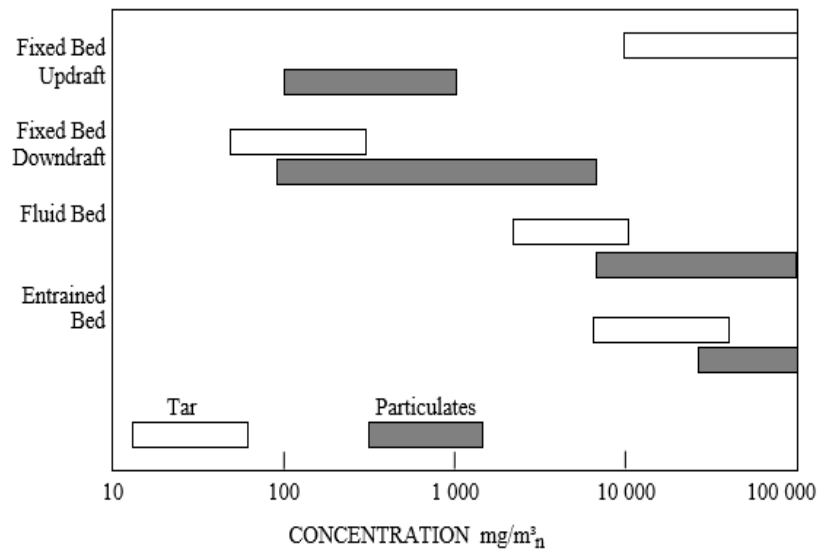


Figure 2.13: Typical Particulate and Tar Loading in Biomass Gasifiers

Source: Stanhlberget *al.* (1998)

2.13.4 Cold and hot gas efficiencies

The Cold Gas Efficiency (CGE) and Hot Gas Efficiency (HGE) provide useful indication of the feedstock energy conversion efficiency accounting for the lower heating value (LHV) of the synthesis gas in the case of the cold gas efficiency and the LHV plus the sensible heat of the syngas and thermal energy inputs in the case of the hot gas efficiency (Sweeney, 2012).

Cold Gas Efficiency (CGE) is defined as the ratio between the chemical energy of the produced gas which is obtained as gas flow rate multiplied by its net heating value and the chemical energy of the biomass fed to the plant which is obtained as biomass flow rate multiplied by its net heating value (Arena, 2012).

Hot Gas Efficiency (HGE), defined as the ratio between the sum of chemical energy and sensible heat of the produced syngas and the sum of chemical energy and sensible heat of the biomass fed to the plant (Arena, 2012).

2.13.5 Carbon Conversion Efficiency (CCE)

CCE is defined as the ratio between the carbon flow rate converted to gaseous products and that fed to the reactor with the biomass. It gives an indication of the amount of unconverted material that must be treated with other technique or sent for disposal, and then provides a measure of chemical efficiency of the process (Arena, 2012).

A carbon conversion efficiency value of 1.0 (100%) indicates that all the feedstock carbon is converted to gaseous product carbon. A carbon conversion efficiency of 0 (0%) indicates that none of the fuel carbon is converted to gaseous carbon product (Sweeney, 2012).

2.14 Biomass Gasification Models

Biomass gasification comprises of set of complex reactions. As a result, some mathematical models were made to predict the performance of the gasifiers (Vaezi *et al.*, 2008).

Simulation, or mathematical modelling, of a gasifier may not give a very accurate prediction of its performance, but it can provide at least qualitative guidance on the effect of design, and operating condition and feedstock parameters. These allow the designer or plant engineer to reasonably optimize the operation or the design of the plant using available experimental data for a pilot plant or the current plant. Simulation can also identify operating limits and hazardous or undesirable operating zones. Modelling provides a less expensive means of experiment but a mathematical model is useless unless it can reproduce real operation with an acceptable degree of deviation (Basu, 2010).

2.14.1 Equilibrium models

Equilibrium models are based on the reactions in the pyrolysis and gasification zones, which are assumed to be in thermodynamic equilibrium. The composition of the producer gas is calculated assuming a fixed reaction temperature and using either heterogeneous (gas-solid) or homogeneous (gas phase) reaction equilibrium (Jayahet *al.*, 2003).

Thermodynamic equilibrium calculations are also used to predict the thermodynamic limits of chemical reactions describing the gasification process. This approach is independent of the gasifier design; hence it is frequently used in studying of the influence of important fuel/process parameters (Vaezi *et al.*, 2008).

Thermodynamic equilibrium may not be really achieved, mainly due to the relatively low operation temperatures (syngas outlet temperatures range from 750°C to 1000°C). However, this model has been used widely (Arnavat, 2011). The models are especially true at the high temperatures that occur on the entrained flow gasifiers, where the reaction temperatures are above 1500K (Vaezi *et al.*, 2008).

Equilibrium models have two general approaches: stoichiometric and non-stoichiometric. The stoichiometric approach requires a clearly defined reaction mechanism that incorporates all chemical reactions and species involved. In the non-stoichiometric approach, no particular reaction mechanisms or species are involved in the numerical simulation. The only input needed to specify the feed is its elemental composition, which can be readily obtained from ultimate analysis data. The non-stoichiometric equilibrium model is based on minimising Gibbs free energy in the system without specifying the possible reactions taking place (Arnavat, 2011).

Due to these assumptions, equilibrium models yield great disagreements under some circumstances. For example at low gasification temperatures its overestimate percentage composition of H₂ and CO and the underestimation of CO₂, methane, tars and. For this reason, modified and corrected equilibrium model used the quasi-equilibrium temperature (QET) approach (Arnavat, 2011).

2.14.2 Kinetic or non-equilibrium models

These models describe the char reduction process using kinetic rate expressions obtained from experiments and permit better simulation of the experimental data where the residence time of gas and biomass is relatively short and it is based on a mechanism of surface reactions in the reduction zone assuming a given residence time and reaction temperature (Vaeziet *al.*, 2008).The gas composition in the gasification zone is calculated from equilibrium data where the flow rate, composition of the solid fuel, the temperature and the composition of the blast gas are known. A heat balance is used to calculate the reaction temperature (Jayahet *al.*, 2003).The accuracy of the model is limited by the availability of data on the initial conditions at the top of the reduction zone; pyrolysis and cracking reactions are not considered because the number of possible pyrolysis products, along with all the possible reactions and intermediate products would make the model very complex. It assumes that all the oxygen from the air inlet is combusted to CO₂ and that the pyrolysis products are completely cracked (Arnavat, 2011).

In addition methane is not considered in the gasification zone, hence these models fail to predict the methane composition precisely. Such models are also not recommended if feasible operating points are not available from experiments or rate models (Jayahet *al.*, 2003).

2.14.3 Steady state rate models

These models compute the gas composition and the temperature profile along the reactor axis. These models include rate equations which consist of mass and energy balances for the heterogeneous and homogeneous reactions and result in a set of ordinary differential equations and algebraic equations (Jayahet *al.*, 2003).

2.14.4 Quasi-steady and transient models

These models do not neglect all the time derivatives. They are based on the mass balances. Transients are calculated using pseudo-steady state assumptions based on the interpolation of the results of the steady state models. These models are used to estimate the effects of step variations in the operating parameters such as solid feed rate or blast gas flow on reactor performance (Jayahet *al.*, 2003).

2.14.5 Kinetics-free models

In these models the reactor is divided into two zones. In the upper or pyrolysis zone, solid reactants are introduced, dried and devolatilized and char is produced here. This char then enters the lower or gasification zone where combustion and gasification reactions take place. The gas composition in the gasification zone is calculated from equilibrium data where the flow rate and composition of the solid fuel and the temperature and the composition of the blast gas are known. A heat balance is used to calculate the reaction temperature (Jayahet *al.*, 2003).

2.14.6 Computational fluid dynamics (CFD)

Computational fluid dynamics can have an important role in the modelling of a fluidized-bed gasifier. CFD models solve a set of simultaneous equations for conservation of mass, momentum, energy, and species over a discrete region of the

gasifier. Therefore they give distribution of temperature, concentration, gas yield and, other parameters within the reactor for a known reactor hydrodynamics (Basu, 2010).

2.14.7 Artificial neural network models (ANN)

ANN is relatively new simulation tool for modelling a gasifier and can deal with complex gasification problems. An ANN model mimics the working of the human brain and provides some human characteristics in solving models. It uses a high-speed architecture of three hidden layers of neurons one to receive the input(s), one to process them, and one to deliver output(s).

It cannot produce an analytical solution, but it can give numerical results. This technique has been used with reasonable results to predict gas yield and composition from gasification of bagasse, cotton stem, pine sawdust, and poplar in fluidized beds, in municipal solid waste; and also in a fluidized bed (Basu, 2010).

CHAPTER THREE

METHODS AND MATERIALS

3.1 Materials and Equipment

The experiments were conducted with a downdraft throated gasifier developed by the National Research Institute for Chemical Technology, Zaria (NARICT) consisting of the reactor, cyclone, filter and air blower. Rice husk was used as biomass feedstock, which was collected from rice milling centre in Zaria.

Other equipment and materials used for the experiment were:

- I. Portable infrared gas analyser (Gasboard 3100P series)
- II. Digital thermometer (UT 350)
- III. K-type (chromel-alumel) thermocouple
- IV. Flow meter (MF5706)
- V. Compressed air (21% O₂, 79 N₂)
- VI. Compressed Oxygen (99.9% purity)
- VII. Silicone gasket maker

3.2 Research Methodology

The methodology employed for this research is presented in Figure 3.1. It involves firstly, characterization of the rice husk used to determine its proximate and ultimate composition. The rice husk composition was used to simulate syngas composition and calorific value using equilibrium model. The experimental gasification was carried out using rice husk with both air and oxygen – enriched air as gasifying agents while varying the flow rates for air and percentage oxygen enrichment for oxygen – enriched gasification. The variation effects on syngas composition, gasification temperature and

calorific value were then monitored. The overall results from the simulation and the experiments were then compared.

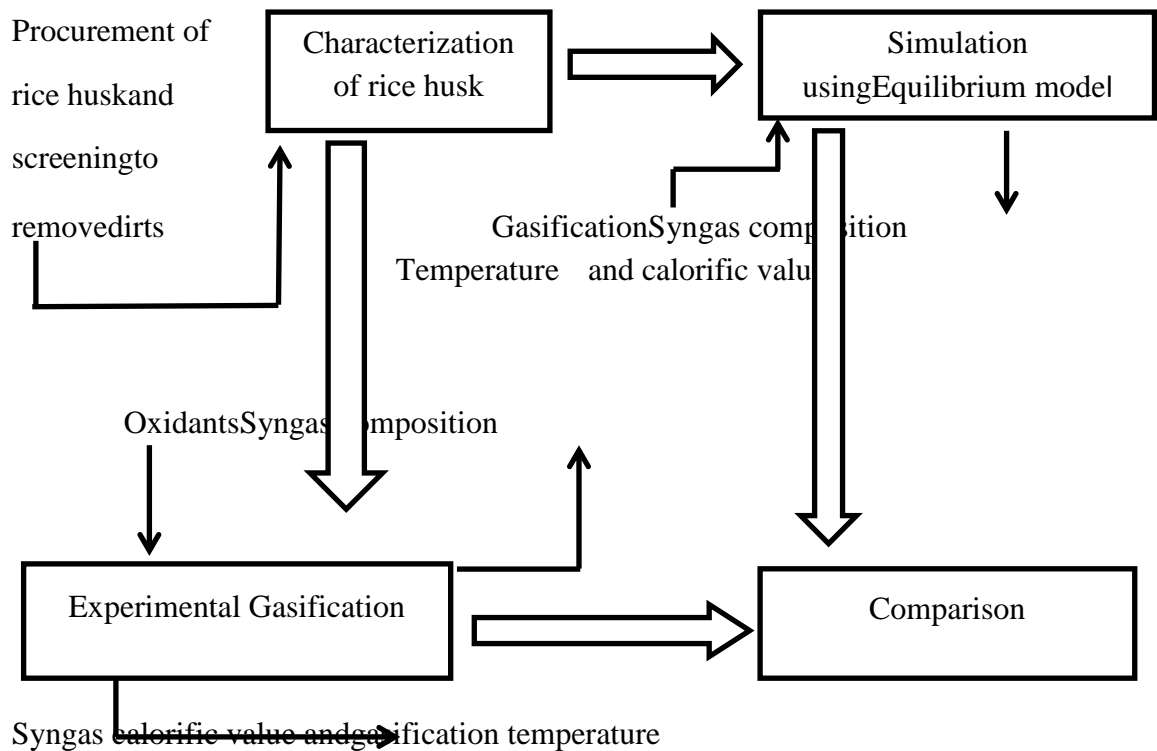


Figure 3.1 Research Methodology

3.2 Rice Husk Characterization

The ultimate and proximate analysis of the rice husk were determined using ASTM methods as shown in Table 3.1 and section 3.2.1 describe the procedures.

Table 3.1: ASTM Methods Used in the Ultimate and proximate analysis of the rice husk

Parameter		ASTM Method
Proximate Analysis	Moisture content	E 871-82
	Ash	D 1102-84.
	Volatile Matter	E 872 - 82.
	Fixed Carbon	Subtracted percentage summation of moisture, ash, and volatile matter from 100 (no number assigned by ASTM)
Ultimate Analysis	Sulphur	E 775-87
	Nitrogen	E 778-87

While for hydrogen, oxygen and carbon as part of the ultimate analysis were determined from correlation developed by Shen,*etal.* (2010) as follows:

$$C = 0.635FC + 0.460VM + 0.095ASH(\text{wt. \%}) \quad (3.1)$$

$$H = 0.059FC + 0.060VM + 0.010ASH(\text{wt. \%}) \quad (3.2)$$

$$O = 0.340FC + 0.469VM + 0.023ASH(\text{wt. \%}) \quad (3.3)$$

3.2.1 ASTM procedures

The procedures for the methods in Table 3.1 were as follows:

- I. Ash: Rice husk was ignited until all the carbons were eliminated at 580 to 600°C. The ash was then expressed as the percentage of residue remaining.
- II. Nitrogen: The determination of nitrogen was carried out according to the ASTM E 778-87, which involved the Kjeldahl-Gunning test method; the nitrogen in the sample was converted into ammonium salts by destructive digestion of the sample with a hot, catalysed mixture of concentrated

sulphuric acid and potassium sulphate. The salts were subsequently decomposed in a hot alkaline solution from which the ammonia was recovered by distillation, and finally determined by acidimetric titration.

- III. Moisture content and volatile matter: Moisture content is determined by the test method given in ASTM standards E 871-82. In this method a weighed sample of the fuel is heated in an air oven at 103°C and weighed after cooling. To ensure complete drying of the sample, the process is repeated until its weight remains unchanged. The difference in weight between the dry and the fresh sample gives the moisture content. Standard E 871-82 specifies that a 50 grams wood sample be dried at 103°C for 30 minutes. It is left in the oven at that temperature for 16 hours before being removed and weighed. Feedstock sample further subjected to higher temperature of about 950°C drives off volatile content leaving behind the fixed carbon and this defined the E 872-82 ASTM method for determination of volatile matter. The measured weight loss established the volatile matter content.
- IV. Sulphur: ASTM E 775 – 87 method involves Eschka procedure, rice husk sample (0.1 mg) and Eschka mixture were ignited together at temperature of $800 \pm 25^\circ\text{C}$ for about 1 hour. Sulphur then precipitated from the resulting solution as barium sulfate (BaSO_4). The precipitate is filtered, ashed, and weighed.

3.3 Equilibrium Modelling Formulation

Thermochemical equilibrium approach was used in predicting the individual fraction of major combustible species of the syngas which is based on equilibrium constants.

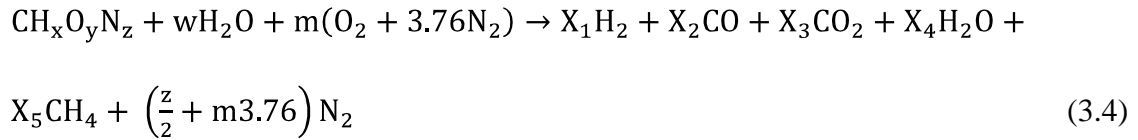
3.3.1 Model assumptions

The main assumptions of the developed model were as follows:

- I. The biomass is composed of carbon, hydrogen, oxygen and nitrogen element only. The presence of sulphur and other minerals is not taken into account (Pandey *et al.*, 2013).
- II. All the carbon content in biomass is converted in gaseous forms and the residence time is enough to achieve thermodynamic equilibrium (Gautam, 2010).
- III. The products taken into account were CO, CO₂, H₂, CH₄, and N₂. The gases are treated as ideal gas and hydrocarbons other than CH₄ were assumed negligible in syngas and were not taken into account. Ash in the feedstock was assumed inert in all gasification reactions (Gautam, 2010).
- IV. The amount of tar in syngas is assumed to be negligible, this assumption is valid since for downdraft gasifier concentration of tar is significantly low compared to other configurations (Gautam, 2010).
- V. The reaction is auto thermal and no external heat source was applied. The reactor is completely adiabatic so that no heat loss can occur from the gasifier. Also, the pressure drop inside the gasifier was assumed to be negligible (Pandey *et al.*, 2013).

3.3.2 Model formulation

The chemical composition of biomass can be taken as CH_xO_yN_z (Pandey *et al.*, 2013) and the global (overall) gasification reaction can be written in the following form (Vaezi *et al.*, 2008):



Here x , y and z are numbers of atoms of hydrogen, oxygen, and nitrogen per one atom of carbon in the feedstock; respectively, w and m are the amounts of water and air per one kmol of feedstock, respectively.

$$w = \frac{M_{\text{bm}} \times \text{MC}}{M_w \times (1 - \text{MC})} \quad (3.5)$$

M_{bm} and M_w are molar mass of biomass and water respectively.

Elemental balance gives:

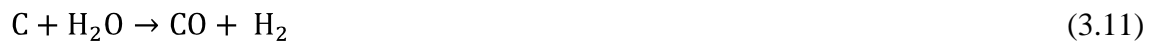
$$\text{C: } X_2 + X_3 + X_5 = 1 \quad (3.6)$$

$$\text{H: } x + 2w = 2X_1 + 2X_4 + 4X_5 \quad (3.7)$$

$$x/2 + w = X_1 + X_4 + 2X_5 \quad (3.8)$$

$$\text{O: } y + w + 2m = X_2 + 2X_3 + X_4 \quad (3.9)$$

The major reactions that occur inside the downdraft reactor are as follows:



Combining the equations 3.10 and 3.11 gives



The equilibrium constant for the reaction are as follows

$$K_1 = (X_5/X_1^2) \quad (3.14)$$

$$K_2 = (X_3X_1)/(X_2X_4) \quad (3.15)$$

The enthalpy of reactants entering must be same as enthalpy of reactants of products leaving the system.

$$H_{\text{reactants}} = H_{\text{products}} \quad (3.16)$$

$$H_{\text{reactants}} = H_{f,\text{biomass}}^0 + w(H_{\text{vap}}) + m(H_{f\text{O}_2}^0 + 3.76H_{f\text{N}_2}^0) \quad (3.17)$$

$$H_{f,\text{biomass}}^0 = \text{LHV} + \sum_{i=1}^n n_i p_i \quad (3.18)$$

Where n_i is the number of moles of species i and p_i is the Products of complete combustion of biomass (kmol) for species i

$$\text{LHV} = 4.187(81C + 300H - 26(O - S) - 6(9H + m)) \text{ (kJ/kg)}, \text{ (Basu, 2010)} \quad (3.19)$$

$$H_{\text{products}} = \sum_{1 \leq i \leq 5} X_i (H_{f,i}^0 + C_{p,i} \Delta_{T-298}) + \left(\frac{z}{2} + 3.76m\right) C_{p,\text{N}_2} \Delta_{T-298} \quad (3.20)$$

T is the gasification temperature.

C_p can be determined using an empirical relation that holds for a wide range of temperature.

$$C_p(T) = c_1 + c_2 T + c_3 T^2 + c_4 T^3 \text{ (kJ/kg)} \quad (3.21)$$

Where c_1 to c_4 are coefficients of specific heat capacity

Equation 3.16 can be simplified into Equation 3.22 as follows:

$$dH_{\text{biomass}} + wdH_{\text{H}_2\text{O}} = X_1 dH_{\text{H}_2} + X_2 dH_{\text{CO}} + X_3 dH_{\text{CO}_2} + X_4 dH_{\text{CH}_4} + X_5 dH_{\text{H}_2\text{O}} + \left(\frac{z}{2} + 3.76m\right) N_2 \quad (3.22)$$

$$dH_i = H_{f,i}^0 + C_{p,i} \Delta_{T-298}$$

$$dH_{\text{H}_2\text{O}(l)} = H_{\text{vap}}$$

$$dH_{\text{biomass}} = H_{f,\text{biomass}}$$

From equation 3.8

$$X_4 = x/2 + w - X_1 - 2X_5 \quad (3.23)$$

From equation 3.7, 3.9 and 3.23

$$y + w + 2m = X_2 + 2X_3 + x/2 + w - X_1 - 2(1 - X_2 - X_3)$$

$$m = 1/2 (X_2 + 2X_3 + -X_1 + 2X_2 + 2X_3 - w + w - x/2 - 2 - y)$$

$$m = 1/2 (-X_1 + 3X_2 + 4X_3 + x/2 - 2 - y) \quad (3.24)$$

From equation 3.14, $X_5 = K_1 X_1^2$ (3.25)

From equations 3.6 and 3.25

$$K_1 X_1^2 + X_2 + X_3 - 1 = 0 \quad (3.26)$$

From equation 3.15

$$X_3 X_1 = K_2 X_2 X_4 \quad (3.27)$$

Substitution of equation 3.6 and 3.23 into 3.27 gives

$$-K_2 (X_1 X_2) + (w + x/2 - 2)K_2 X_2 + 2K_2 X_2^2 - X_3 X_1 + 2K_2 X_2 X_3 = 0 \quad (3.28)$$

Substitution of equation 3.6, 3.23, 3.24 into 3.22 gives

$$AX_1 + BX_2 + CX_3 + DX_4 + E \quad (3.29)$$

Where

$$A = dH_{H_2} - dH_{H_2O(v)} - ((3.64 + z/2)/2)dN_2$$

$$B = dH_{CO} + 2dH_{H_2O(v)} - dH_{CH_4} + ((3.64 + z/2)3/2)dN_2$$

$$C = dH_{CO_2} + 2dH_{H_2O(v)} - dH_{CH_4} + ((3.64 + z/2)4/2)dN_2$$

$$D = dH_{H_2O(v)} - dH_{H_2O(l)}$$

$$E = dH_{CH_4} + 1.26dH_{H_2O} + ((3.64 + z/2)/2)(x/2 - 2 - y)dN_2 - dH_{biomass}$$

K_1 (Zainalet *tal.*, 2001) is given by

$$\ln K_1 = 7082.848/T + (-6.567) \ln T + (7.466e^{-3}/2) T - (2.164e^{-6}/6) T^2 + 0.701e^{-5}/2T^2 + 32.541 \quad (3.30)$$

K_2 (Htutet *tal.*, 2015) is given by:

$$K_2 = \exp(4276/T - 3.961) \quad (3.31)$$

The coefficients X_1 to X_3 and equivalence ratio can now be solved by solving equations 3.26, 3.28 and 3.29 using Newton's Raphson method in MATLAB by supplying elemental compositions of rice husk and moisture content to determine syngas

composition. Once the input parameters are defined the program automatically calculates the equivalence ratio to maintain the preset temperature with respect to moisture content.

3.4 Experimental Procedure

The gasifier is a throated downdraft with an internal diameter of 30cm and a height of 82cm. Each experimental run was started by loading the gasifier with the rice husk with minimum load as the grate capacity of height 10cm and diameter 36cm. After charging the biomass, sealing is normally done using silicone gasket maker to prevent leakages.

The start-up procedure involved ignition of the rice husk through the ignition port, air supply through the port to sustained the ignition with the help of air blower reserved in negative pressure direction resulting in driving air out of the gasifier, this normally lasted for 10 minutes, the ignition port is then closed. For experiment using air as gasifying agent air blower was then used in a positive pressure direction to supply air through the air supplying port into the gasifier, 0.7, 3.0 and 6.4 L/min flow rates of air were used and were varied using the flow controller, due to the limitation of the air blower, the experiment was unable to carried out above air flow rate of 6.4 L/min. While for the experiment involving oxygen enriched- air as gasifying agent instead of using air blower to supply air to the system, compressed air and oxygen were mixed to increase the percentage oxygen in air, 30, 40, 50, 60, 80 and 100% enrichment were used for the experiment, a constant flow rate of 10 L/min was used for all the enrichment levels.

Gasification reaction proceeds with interaction between the gasifying agent (either air or oxygen enriched- air) and the rice husk inside the gasifier. In the gasifier, the rice husk undergoes several different processes; drying, pyrolysis, combustion, and reduction in a sequential order from the top of the gasifier. Combustion takes place at the oxidation

zone, which is where the ignition takes place providing the heat needed for other gasification reactions which are mostly endothermic in nature. Drying and pyrolysis reactions takes place above the oxidation zone, where the biomass is then dried and cracked to release gases, char and tar. The char particles undergo further reactions with several gases to yield the desired gaseous products at reduction zone which is below the oxidation zone. The syngas is then withdrawn from the bottom of the gasifier, which is the reason the gasifier is termed “downdraft”. Ash component generated from gasification reaction falls to the lower part through a perforated grate and collected through the ash collection part.

The syngas produced was then passed through a cyclone and a filter for gas cleaning to remove particulates. The cleaned syngas is then sampled to the online gas analyser where CO, CO₂, H₂, CH₄, O₂ as composition and calorific value were displayed and recorded with time. Figure 3.2 shows a schematic diagram of the experimental set-up of the gasification system. The oxidation zone temperature was also monitored and recorded with time using the K-type thermocouple as temperature sensor and the digital thermometer as temperature indicator and recorder.

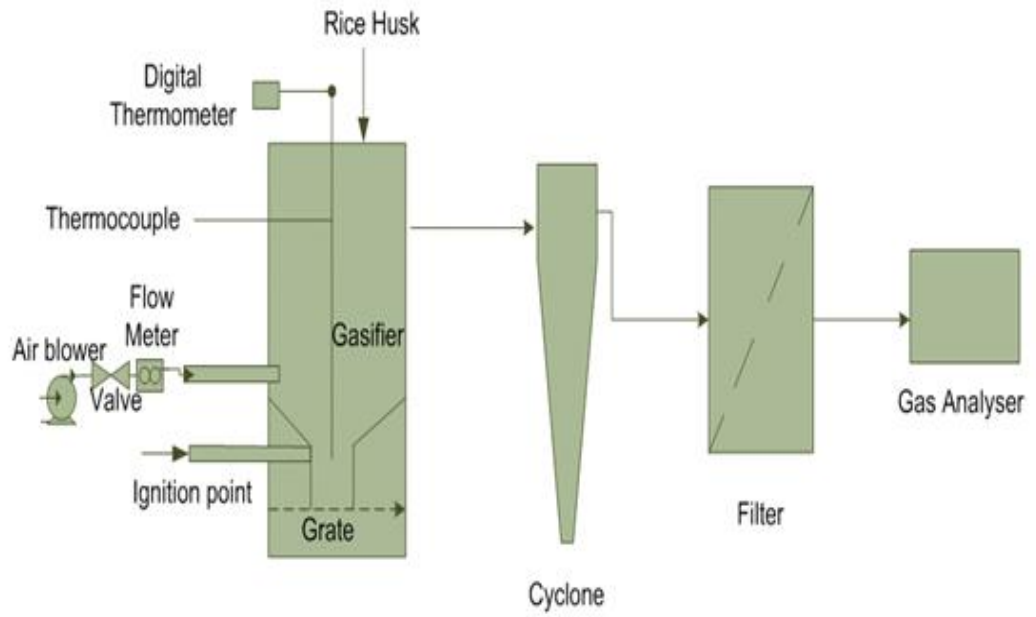


Figure 3.2: Schematic Diagram of the Experimental Set-up of the Gasification System

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Characterization of Rice Husk

Figures 4.1 and 4.2 show the chemical composition of the rice husk in terms of proximate and ultimate analysis respectively. The chemical composition of any biomass has impact on the gasification behaviour of the biomass and the syngas composition and quality.

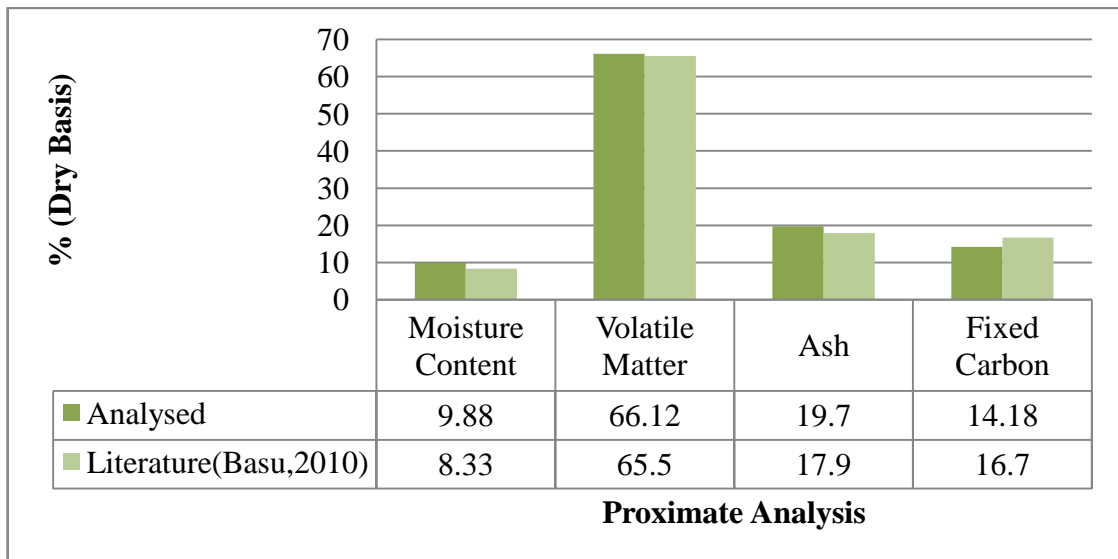


Figure 4.1: Proximate Analysis of Rice Husk

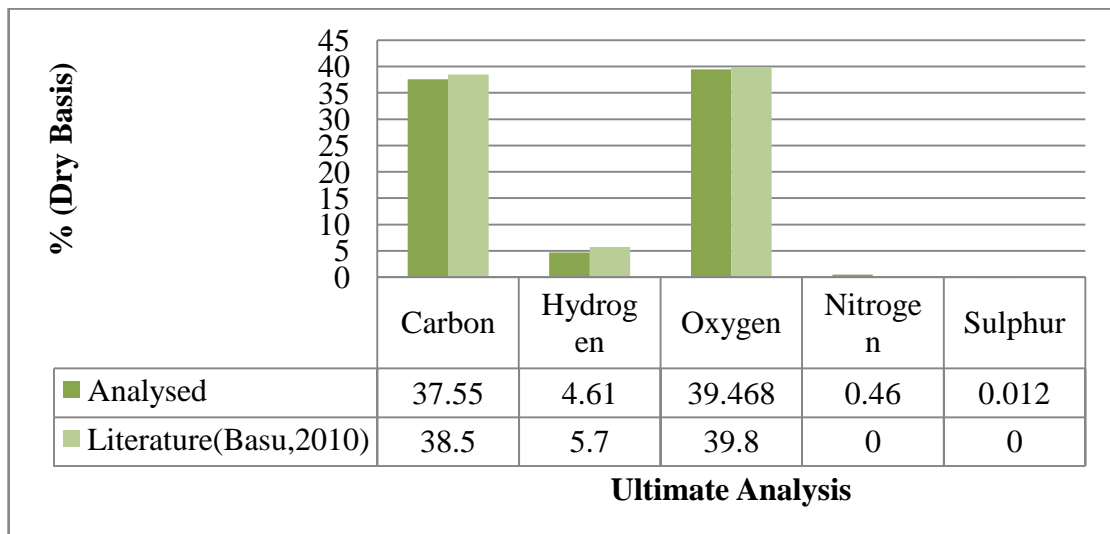


Figure 4.2: Ultimate Analysis of Rice Husk

Moisture content was found to be 9.88 % (Dry basis) and it is desired to be low because the higher the moisture content of the rice husk, the more carbon monoxide (CO) is consumed by the water-gas shift reaction to produce CO₂ and H₂ as in equation (4.4). However, H₂ is produced, which is one of the desired syngas components and the reaction is exothermic which will provide more heat for other reactions which are mostly endothermic. But the H₂ produced is insignificant compared with the amount of CO loss with increase in moisture content. In addition, the small amount of heat gained due to the exothermic behaviour of the water-gas shift forward reaction is less than that will be required to evaporate the moisture. The overall effect is decrease in temperature, which favours the exothermic reaction (Gautam, 2010). Equations (4.1) to (4.5) describe the main reactions occurring in a gasification system namely; as water-gas, boudouard, methanation, water –gas shift and steam reforming.



Biomass with moisture content above 30% makes ignition difficult due to the need to evaporate the additional moisture before combustion/gasification can occur (Arnavat, 2011). Ash was also found to be 19.7 % (dry basis) from Figure 4.1. When ash content is above 5%, slagging occurs due to formation of clinkers which results into gasifier operational challenges. However, successful gasification with ash-content up to 25% is possible with effective ash discharging mechanism (Gautam, 2010). Volatile matter was found to be 66.12% (dry basis) and the higher its percentage, the more pyrolysis gases and tar will be generated. Fixed carbon was also found to be 14.18% (Dry basis) from

Figure 4.1 and any gasification reaction desired this value to be high because it is the carbon left for gasification reactions after devolatilization has occurred.

Figure 4.2 shows the elemental composition which has effect on syngas produced from rice husk and it was found to be in weight percent dry basis as 37.54, 4.61, 37.67, 0.46 and 0.012 for carbon, hydrogen, oxygen, nitrogen and sulphur, respectively. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio. A higher elemental carbon will increase the amount of carbon that will be available for gasification reaction. Higher oxygen content will require less oxygen as oxidant, however its presence in higher amount will limit the percentage of carbon and oxygen in the biomass. The amount of sulphur and nitrogen oxides that will be generated when the syngas is burned depends on appreciable percentage of sulphur and nitrogen content in the biomass. The ultimate analysis of the rice husk shows a negligible amount of sulphur and nitrogen.

The proximate and ultimate values were used in evaluating other parameters, which include chemical formula of rice husk available for gasification which was calculated as $\text{CH}_{1.47}\text{O}_{0.75}\text{N}_{0.01}$ detail calculation was presented in (Appendix A), the stoichiometric amount of air for complete combustion and higher heating value of the rice husk which were calculated from empirical relations as 4.393 Kg air/Kg dry rice husk from $[0.1153\text{C} + 0.3434(\text{H} - \text{O}/8) + 0.0434\text{S}]$ kg/kg dry fuel (Basu, 2010) and 14457 KJ/Kg dry rice husk from $349.1\text{C} + 1178.3\text{H} + 100.5\text{S} - 103.4\text{O} - 15.1\text{N} - 21.1\text{ASH}$ KJ/Kg (Basu, 2010) respectively.

4.2 Equilibrium Modelling of Rice Husk Gasification Using Air as the Gasifying Agent

Thermodynamic equilibrium models are mathematical calculations suitable for studying the influence of biomass composition and process parameters such as temperature and equivalence ratio (describes to what extent gasification is taking place with deficient of oxygen) to predict the potential syngas composition without providing appropriate gasifier dimensions. The gas composition is calculated assuming a fixed reactor temperature and that gasifier reactions are in equilibrium. In this work, a model was developed based on thermodynamics, mass and energy balances presented in the research methodology section. The model equations were solved using MATLAB with temperature inputs between 500 to 1100 °C. Simulated output parameters were syngas composition, desired syngas components which represents the combination of combustible gases (H₂, CO and CH₄) in the syngas and calorific value. The detailed simulated results were presented in (Appendix D) together with the MATLAB codes while Figures 4.3 and 4.4 give the summary.

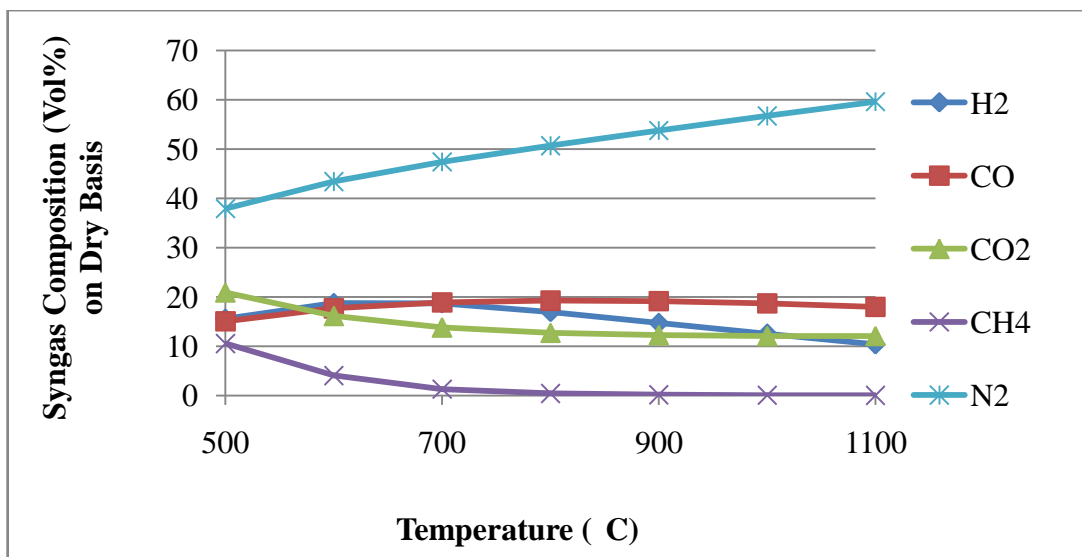


Figure 4.3: Simulation Results of Rice Husk Gasification using Equilibrium Modelling

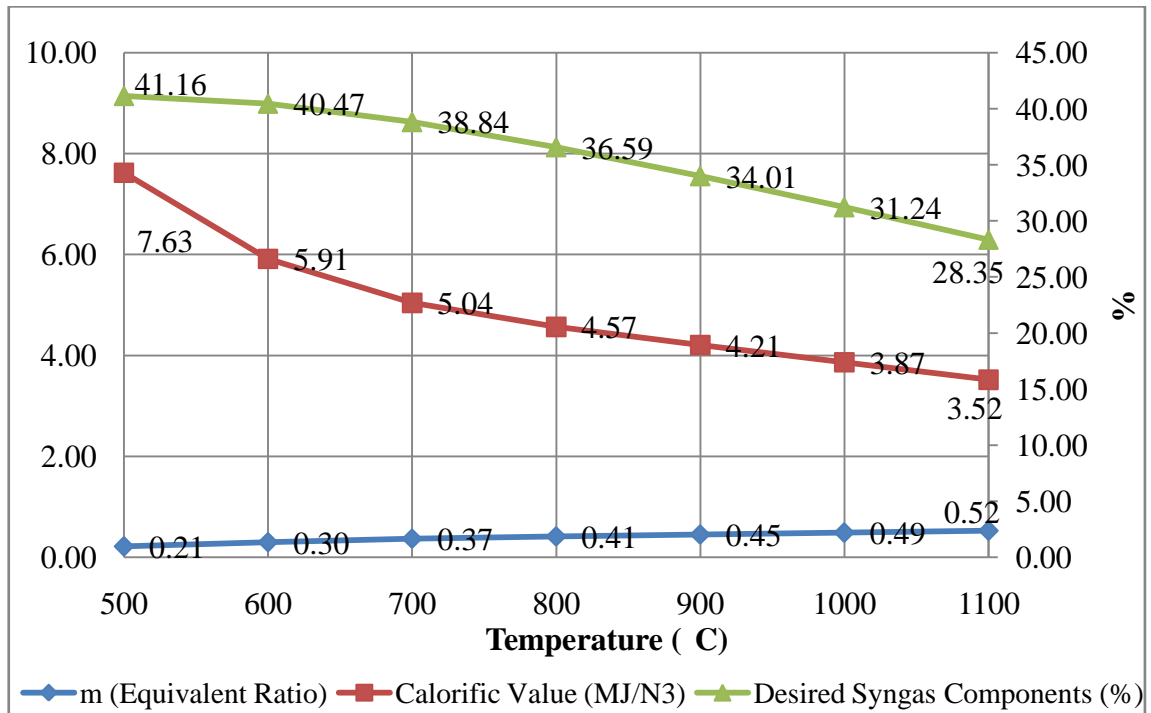


Figure 4.4: Simulation Results of Variation of Equivalence Ratio and Syngas Calorific Values with Temperature of Rice Husk Gasification

Figures 4.3 and 4.4 show model simulation results of the rice husk gasification using air as the gasifying agent between reaction temperatures of 500 to 1100 °C. It is observed that the diluent nature of N₂ in the syngas increases with temperature from 38.50 to 60.02%. Wu *et al.*, (2009) reported that as temperature increases in air gasification, N₂ in the syngas also increases, resulting in lowering the heating value of the syngas. H₂ increases between 500 and 600 °C, from 15.45 to 18.56% and decreases from this point to 10.10% at 1100 °C, with the best value recorded at 600 °C as 18.56%. CO increases from 14.11% at 500 °C to a peak value of 18.72% at 800 °C and then decreases to 17.50% at 1100 °C. CO₂ decreases gradually from 21.19% at 500 °C to 12.33% at 1000 °C, and then increases to 12.36% at 1100 °C. This is so because oxidation, boudouard backward and water-gas shift reactions that produce CO₂ are all exothermic

reactions which are favoured at lower temperatures and at 1100 °C the reaction begins to shift from gasification to combustion due to increase in oxygen. CH₄ also decreases from 10.46% at 500 °C to 0.02% at 1100 °C, because the reactions that produce methane from methanation and steam reforming are favoured at lower temperature because of their exothermic nature. From Figure 4.4 it is observed that the equivalence ratio which represents how oxygen is supplied for the gasification increases as temperature is increased from 0.22 at 500 °C to 0.53 at 1100 °C, this so because as equivalence ratio increases, it rises the amount of oxygen that will be available for the exothermic oxidation which then increases the temperature. The calorific value and desired syngas component decreases as the temperature is increased between 500 °C and 1100 °C, from 7.46 to 3.43 MJ/m³ and 40.02% to 27.62%, respectively. This could be attributed to decrease in both H₂ and CH₄ as the temperature is increased. The best syngas composition was obtained at 800 °C having the highest CO, with composition of 18.72 CO%, 16.68% H₂, 13.05% CO₂, 0.39% CH₄, 4.47 MJ/m³ calorific value and 0.42 equivalence ratio.

4.3 Experimental Rice Husk Gasification Using Different Air Flow Rates

Composition and calorific value of a syngas are the major key parameters that determine the quality of the syngas. However, these parameters are largely dependent on gasifying agents (air, steam, oxygen) and the process operating parameters (gasification temperature, equivalence ratio, types of biomass). This section investigates the effects of air as gasifying agent and its variation on temperature, equivalence ratio, composition and calorific value of the syngas. Three sets of air flow rates were used as 6.4, 3 and 0.7 L/min.

In any gasification, the desire is to supply the system with deficient of oxygen and for this reason the oxygen composition in the syngas should be kept as low as possible. The

trend from Figures 4.5, 4.6 and 4.7 revealed that oxygen composition reduces with time, with reduction from maximum to minimum value of 20.61 to 2.5%, 21.89% to 7.88%, 20.85 to 9.85% for flow rates of 6.4, 3 and 0.7 L/min, respectively after 50 minutes of gasification operation. This shows that oxygen in the syngas reduces with increase in air flow rate.

In gasification, different reactions are occurring, some are exothermic and some are endothermic, thereby influencing the composition of the syngas. From Figure 4.5 (variation of composition and calorific value of syngas at 6.4 L/min), it is observed that CO increases with time to a peak value of 12.07% at 30 minutes, then decreases with time from this point to 7.12% at 50 minutes, while CO₂ increases with time beginning from 1.17 to 14.44% at 50 minutes. These two components (CO and CO₂) are vital in telling whether the reactions at any point are more of combustion or gasification. The rise and fall of CO is due to the fact that at higher temperatures more biomass is combusted resulting in less material to gasify, thereby producing more CO₂ than CO. This starts at the point CO reaches its peak value (James *et al.*, 2014; Wu *et al.*, 2009). The same trend is observed with CH₄ and H₂ as that of CO, CH₄ increases from 1.17% to a peak value of 2.54% at 30 minutes and then decreases to 1.81% at 50 minutes. H₂ increases from 0.02% at the beginning to maximum value of 1.18% after 20 minutes and then decreases to 0.51% at 50 minutes. Similar variations of syngas composition with time were recorded with air flow rates of 3 and 0.7 L/min. The best composition is considered at point where CO is higher than CO₂, 6.4 L/min recorded the overall best composition as 10.83% CO, 9.51% CO₂, 2.12% H₂, 1.18% CH₄ after 20 minutes. The least was observed at 0.7 L/min as 5.19% CO, 4.59% CO₂, 0.69% CH₄, 0% H₂ after 40 minutes. Best composition of 6.39% CO, 6.36% CO₂, 1.3% H₂, 0.5% CH₄ was achieved at 3 L/min air flow rate after 30 minutes.

Syngas calorific value is a function of the combustible gases (H_2 , CO and CH_4) in the syngas and is referred to as desired syngas components (DSC). Individual component of syngas has calorific value in MJ/Nm^3 of 37.1, 13.1, 11.2 for CH_4 , CO and H_2 respectively (Tasma *et al.*, 2009). So the higher the percentage combination of these three components the higher the calorific value of the syngas. On the other hand CO and O_2 have no calorific values and their presence in syngas in higher percentage lessens the calorific value of the syngas. Highest syngas calorific values were recorded at the highest desired syngas components (DSC) of 15.62, 9.31 and 6.20% as 2.54, 1.48 and 0.95 MJ/Nm^3 syngas calorific values were observed for 6.4, 3.0 and 0.7 L/min air flow rates, respectively. This implies that the syngas calorific value increases with increase in the air flow rate within the chosen rates used during the experiment.

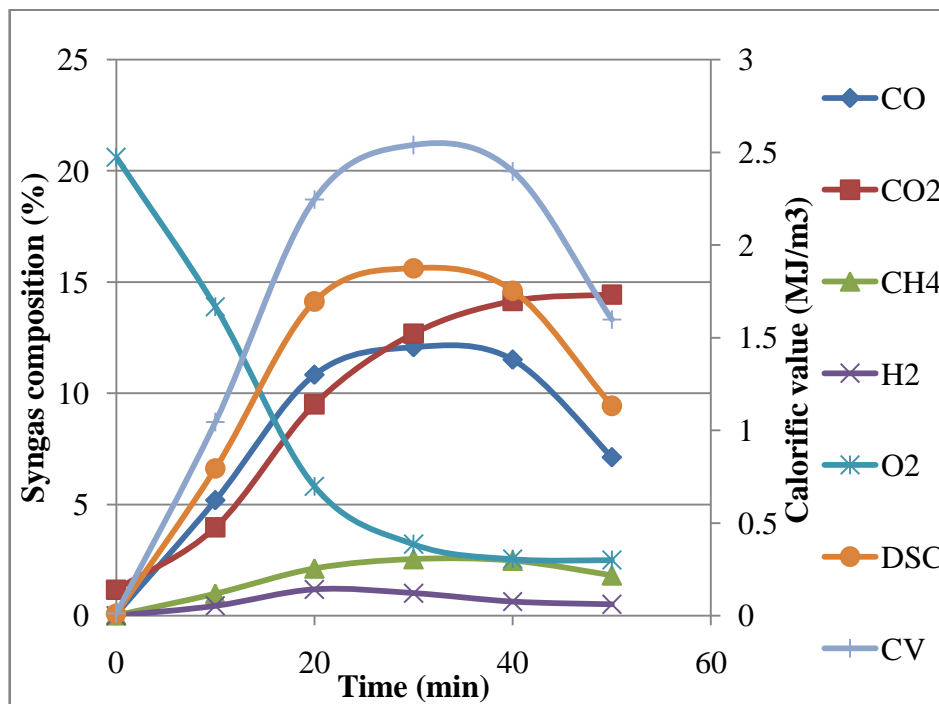


Figure 4.5: Variation of Composition and Calorific Value of Syngas with Time at 6.4 L/ min Air Flow Rate

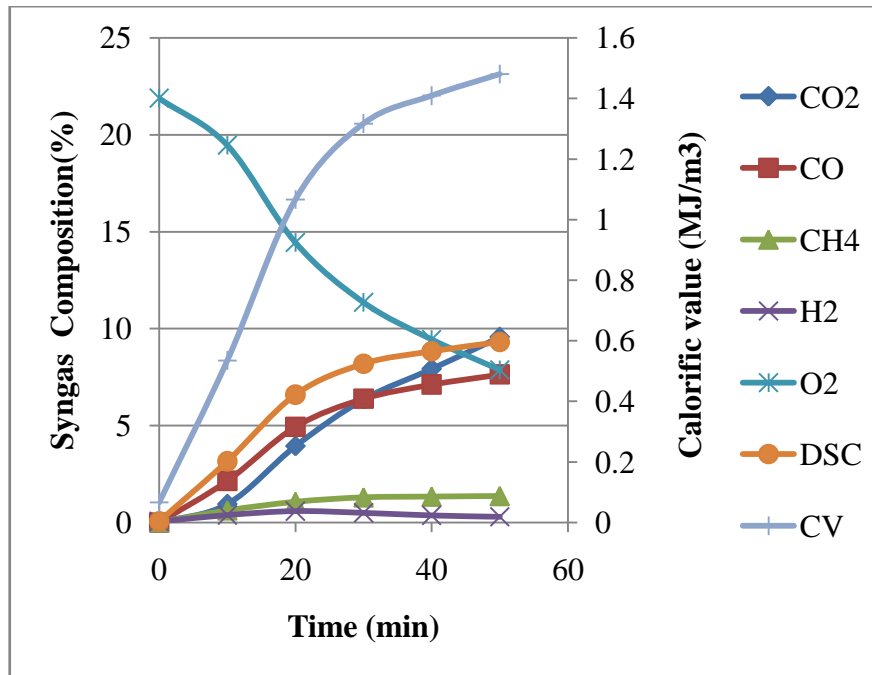


Figure 4.6: Variation of Composition and Calorific Value of Syngas with Time at 3.0 L/ min Air Flow Rate

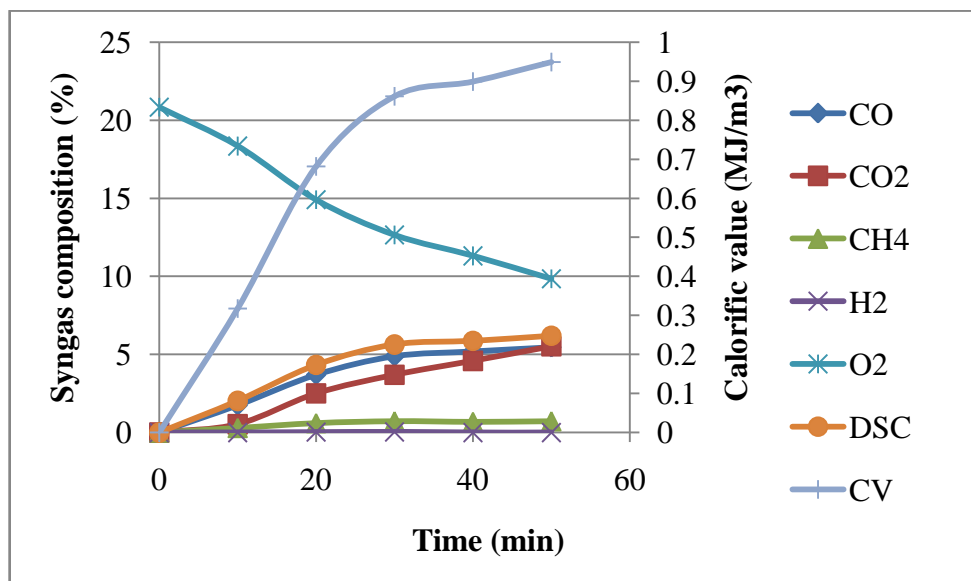


Figure 4.6: Variation of Composition and Calorific Value of Syngas with Time at 0.7 L/ min Air Flow Rate

Table 4.1 shows relationship between the desired syngas components, calorific value, average oxidation temperature and equivalence ratio. Equivalence ratio is a parameter that measures how gasification is supplied with less oxidant than would be required for stoichiometric combustion. It is defined as the ratio of the amount of oxygen

(air) supplied and the amount of oxygen (air) needed for stoichiometric combustion of biomass feedstock. A value of one (1) indicates combustion and a value of zero (0) indicates pyrolysis, while gasification takes place in between the two values. The averages temperatures recorded were 567, 250, and 178°C for flow rates of 6.4, 3.0 and 0.7 L/min respectively. It can be deduced that oxidation temperature in gasification increases with air flow rate, which is justified because in an auto-thermal gasification, heat required for the system is supplied by the exothermic heat released at the oxidation zone. Equivalence ratio followed the same trend with temperature, that is, it increases linearly with increased in temperature. This is because more air input translates to higher equivalence ratio and more combustion, which in turn elevates the temperature of the gasifier (Detailed calculations of equivalence ratio were presented in Appendix E)

Table 4.1: Temperatures and Calorific Values at Different Air Flow Rate

Air Flow rate (L/min)	6.4	3	0.7
Calorific Value (MJ/m ³)	2.54	1.48	0.98
Temperature (°C)	567	250	178
Desired Syngas Components (%)	14.13	8.19	5.88
Equivalence ratio	0.128	0.062	0.014

4.4 Comparison between Modelling and Experimental Results

The model developed was validated by comparison with the experimental data obtained in this work and literature experimental data using the universal testing method of root mean square error (RMSE):

$$\sqrt{\frac{\sum_i^N (\text{Experimental} - \text{model})^2}{N}} \quad (4.6)$$

The RMSE was obtained as 7.58 with individual values as 7.89 CO, 14.56 H₂, 3.54 CO₂, 0.79 CH₄ and 1.74 for calorific value for experimental data of this work. While for the literature experimental data, 2.37 RMSE was calculated with individual values as 3.82 CO, 3.08 H₂, 0.15 CO₂, and 2.01 CH₄ and 0.06 for calorific value. The comparison in Table 4.2 was done at 800 °C except for (Yoon, 2012) experiment which was conducted between 600- 850 °C and the present experiment, where an average temperature of 567°C was used, which represents the best syngas composition at the highest flow rate of 6.4 Lit/min. During the experiment conducted using air as the gasifying agent, this could be the reason for higher value of RMSE for the present experiment. Another reason is that 0.128 equivalence ratio is less than the predicted value suggested by the present model of 0.42, which is due to research limitation of not being able to go beyond 6.4 L/min air flow rate. It was observed that the model under predicts the amount of CH₄ and over predicts the amount of H₂ in comparison with the experimental data. Previous works reported similar cases (Pandey *et al.*, 2013; Jarunthammachote and Dutta, 2007). The deviation in the CH₄ value is attributed to equilibrium constant of the methanation reaction which tends to zero at the elevated temperatures prevailing in the reduction zone (Vaezi *et al.*, 2008). The reaction therefore tends to deviate from the equilibrium condition. However the other reaction that is, water gas shift that influences the composition of the gas is expected to reach equilibrium at high temperature (800 °C), (Barman *et al.*, 2012).

Table 4.2: Comparison between Model and Experimental Values

Syngas Gas	ER	CO	H ₂	CO ₂	CH ₄	Caloric Value	RMSE
Components	(MJ/m ³)						
Literature Model (Zainal, 2001)	-	16	18.43	-	0.84	4.07	-
Present Model	0.42	18.72	16.68	13.05	0.39	4.47	-
Literature Experiment (Yoon,2012)	0.45-0.6	14.9	13.6	12.9	2.4	4.53	2.37
Present Experiment	0.128	10.83	2.12	9.51	1.18	2.54	7.58

4.5 Experimental Gasification of Rice Husk Using Oxygen-Enriched Air

This section analyzes the gasification of rice husk with oxygen-enriched air as the gasifying agent. 30, 40, 50, 60, 80 and 100% oxygen enrichment in air were used. It was noticeable from Figure 4.8 that as oxygen enrichment in air increases from 30 to 100%, temperature and equivalence ratio also increased from 449 °C to 1015 °C and 0.289 to 0.955, respectively. This is so because as enrichment is increased, oxygen availability for oxidation reaction also increases by increasing the density and mass flow rate of the air, resulting in overall effect of increased equivalence ratio and subsequent rise in temperature inside the gasifier.

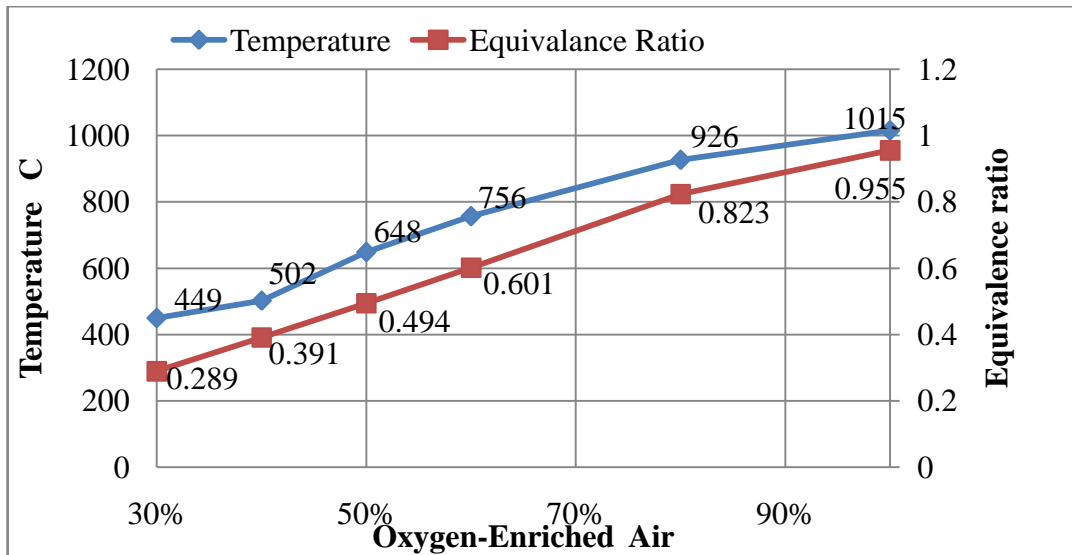


Figure 4.8: Variations of Temperature and Equivalence Ratio with Oxygen Enrichment

Figure 4.9 shows the summary of results of the performance of rice husk gasification with oxygen-enriched air. It is observed that 100 % enrichment gave the best desired syngas components and calorific value but lowest CO to CO₂ ratio. Ordinarily this could have been the best point of operation but having had the lowest CO to CO₂ ratio of 0.56, it means the reaction is more of combustion than oxidation, therefore the best operating point was considered at 50% enrichment which has the highest CO to CO₂ ratio of 1.63, equivalence ratio of 0.448, desired syngas components of 24.34%, composition of 19.8% CO, 12.16% CO₂, 2.26% H₂ and 2.28% CH₄.

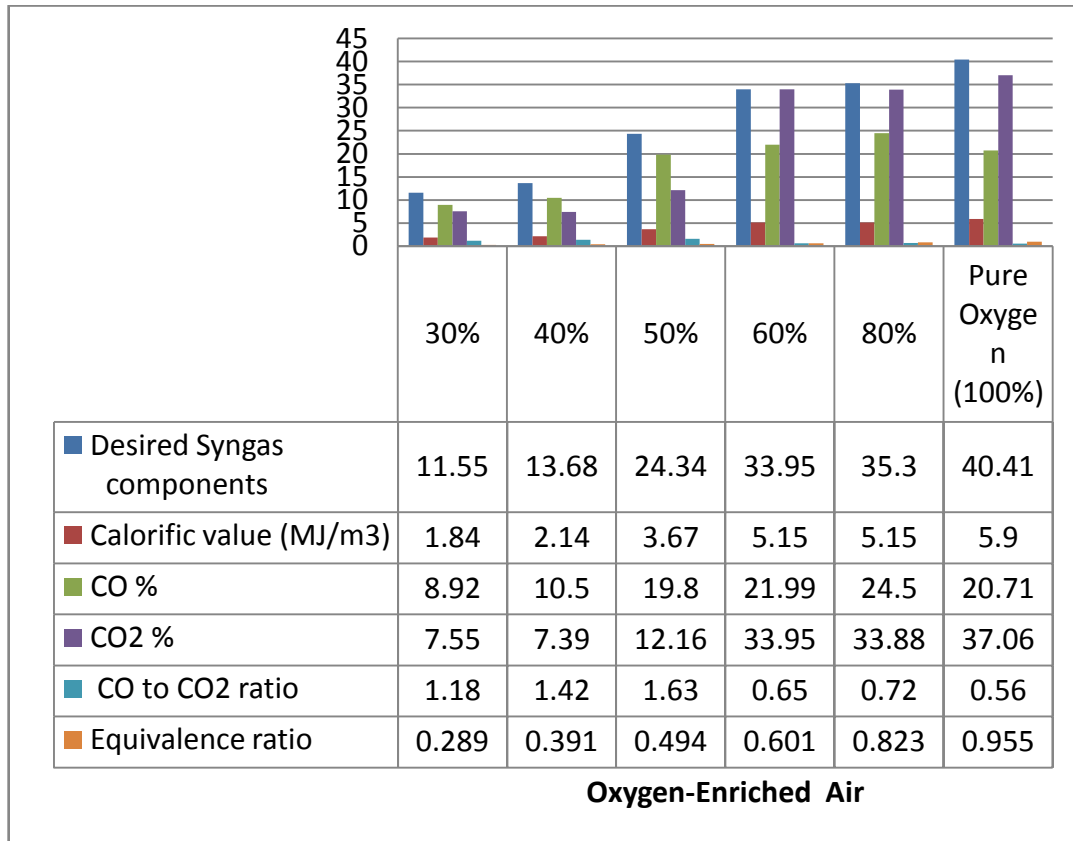


Figure 4.9: Summary of Performance of Rice Husk Gasification with Oxygen-Enriched Air

4.6 Overall Performance Analysis of the Gasification Process

This section analyse the performance of the rice husk gasification using both air and oxygen- enriched air as gasifying agents. The analysis was done using two parameters; Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE). The CCE which is defined by equation (4.7), (Makwana *et al.*, 2014) measures the chemical efficiency of the process (Arena, 2012), a value of 1.0 (100%) indicates total conversion of the carbonaceous feedstock into gaseous products, while a value of 0 (0%) indicates none of the fuel carbon is converted (Sweeney, 2012). A comparison between the chemical energy of the syngas and that of biomass fuel is indicated by cold gas efficiency, which is defined by equation (4.9), (Makwana *et al.*, 2014)

$$CCE = \frac{Y(CO\% + CH_4\% + CO_2\%) \times 12}{22.4 \times C\%} \times 100 \quad (4.7)$$

Where Y = dry gas yield (Nm^3/kg) expressed by equation (4.8), $CO\%$, $CH_4\%$ and $CO_2\%$ are the composition inside the syngas.

$$Y = \frac{Q_a \times N_a}{W_b(1 - X_{ash}) \times N_p} \quad (4.8)$$

Where Q_a is the flow rate of the gasifying agent supplied (Nm^3/h), W_b is the mass flow rate of biomass (kg/h), N_a is the nitrogen in gasifying medium and N_p is the nitrogen in syngas.

$$CGE = \frac{Y \times LHV_{gas}}{LHV_{biomass}} \quad (4.9)$$

Where LHV_{gas} and $LHV_{biomass}$ are the heating values of the syngas and biomass in MJ/m^3 and MJ/Kg respectively.

Table 4.3 shows the summary of the performance analysis of rice husk gasification using both air and oxygen-enriched air. It can be deduced from the table that LHV, CCE and CGE increased with increase in air flow rate for air gasification and with oxygen enrichment for the case of oxygen-enriched air gasification. For air gasification highest CCE and CGE was achieved as 21.27 and 12.55%, respectively with the highest air flow rate of 6.4L/min, while for oxygen-enriched air gasification, 50% oxygen enrichment in air gave the best values of both CCE and CGE as 46.72 and 26.24%, respectively. The parameters were not considered at 60, 80 and 100% enrichment because CO/CO_2 was less than one (1) for each.

Table 4.3 Performance Analysis of Gasification

Gasifying Agent	ER	CCE	LHV	CGE	CO/CO ₂
		(%)	(MJ/m ³)	(%)	
Air (l/min)	0.7	0.014	1.14	0.90	0.51 1.13
	3.0	0.062	7.03	1.32	3.46 1.00
	6.4	0.128	21.27	2.53	12.55 1.14
Oxygen enriched air (%)	30	0.289	26.50	1.84	14.41 1.12
	40	0.391	25.92	2.14	14.62 1.42
	50	0.494	46.72	3.67	26.24 1.63
	60	0.601	-	5.15	- 0.65
	80	0.823	-	5.15	- 0.72
	100	0.958	-	5.90	- 0.56

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 CONCLUSIONS

The following conclusions are drawn from the gasification study carried out using downdraft gasifier with rice husk feedstock:

1. Increase in air flow rate (0.7, 3.0 and 6.4 L/min were considered) during air gasification favours oxidation temperature, equivalence ratio, syngas composition, and calorific value. The best syngas composition recorded using air as the gasifying agent was at 6.4 L/min with composition of 10.83% CO, 9.51% CO₂, 2.12% H₂ and 1.18 CH₄%, desired syngas composition of 14.13 % and equivalence ratio of 0.128, with an average temperature of 567°C and 2.75 MJ/Nm³ calorific value.
2. A mathematical model was successfully developed using equilibrium approach to predict rice husk gasification using air as gasifying agent between 500 and 1100 °C. The results of the model suggested an optimum temperature at 800 °C and equivalence ratio of 0.42 with syngas composition of 18.72 CO%, 16.68% H₂, 13.05% CO₂, 0.39% CH₄, and 4.47 MJ/m³ calorific value.
3. Validation of the model developed was done with the best results obtained from rice husk air gasification and gave a root square mean error value of 7.58.
4. For oxygen enriched- air rice husk gasification, 30 to 100% oxygen enrichment in air were considered. It was found within this range that temperature, equivalence ratio and calorific value increased linearly with increase in enrichment. The CO to CO₂ ratio was found to be greater than one and also increasing linearly between 30 to 50% enrichment, while decreasing linearly and less than one from 60 to 100% enrichment. The best point was considered at 50% oxygen enrichment in air

having the highest CO to CO₂ of 1.63 with equivalence ratio of 0.494, desired syngas of 24.34%, syngas composition of 19.8% CO, 12.16% CO₂, 2.26% H₂, 2.28% CH₄, and calorific value of 3.67 MJ/m³.

5. Performance analysis of rice husk gasification using both air and oxygen-enriched air as gasifying agents showed that carbon conversion efficiency (CCE) and cold gas efficiency (CGE) increased with increase in air flow rate for air gasification and with oxygen enrichment for the case of oxygen-enriched air gasification. For air gasification highest CCE and CGE were achieved as 21.27 and 12.55%, respectively with the highest air flow rate of 6.4L/min, while for oxygen-enriched air gasification, 50 % oxygen enrichment in air gave the best values of both CCE and CGE as 46.72 and 26.24%, respectively.

5.2 RECOMMENDATIONS

The following recommendations are suggested for further studies:

1. Other model approaches like non-equilibrium and artificial neural networks should be employed to see if lower error can be achieved and the modification of the equilibrium model.
2. The air blower only supplied maximum air flow rate of 6.4 L/min equivalence to equivalence ratio of 0.128 during gasification using air as gasifying agent creating a research limitation, because model suggested an optimum equivalence ratio of 0.42. Therefore further research is recommended at higher flow rates that will provide equivalence ratio up to and beyond the best simulated value.
3. During the oxygen-enriched air gasification the flow rates were kept constant while varying the percentage oxygen of the gasifying agent. Further research is recommended to be carried out on gasification using oxygen-enriched air by varying both the flow rate and percentage oxygen enrichment. This will lead

to having different equivalence ratio at each enrichment level, thereby giving a better option to optimize the process.

4. Research is strongly recommended for the possibility of separating carbon dioxide in syngas and use as supplementary gasifying agent of the gasification system.

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APPENDIX A

Chemical Formula of Rice Husk Calculation.

The dry biomass fuel can be expressed by a generalized molecular formula $CH_xO_yN_z$ where the subscripts x, y and z are molecular weight of hydrogen, oxygen and nitrogen per molecular weight (Barman,*et al.*,2012).

Results from ultimate analysis

$$C = 37.55 \text{ wt\%,} = 37.55/12 = 3.13 \text{ moles}$$

$$H = 4.61 \text{ wt\%,} = 4.61/1 = 4.61 \text{ moles,}$$

$$x = 4.61 \text{ moles} / 3.13 \text{ moles} = 1.47$$

$$O = 37.67 \text{ wt\%,} = 37.67/16 = 2.35 \text{ moles}$$

$$y = 2.35 \text{ moles} / 3.13 \text{ moles} = 0.75$$

$$N = 0.46 \text{ wt\%,} = 0.46/14 = 0.03$$

$$z = 0.03 \text{ moles} / 3.13 \text{ moles} = 0.01$$

Molecular formula of the rice husk available for gasification = $CH_{1.47}O_{0.74}N_{0.01}$

APPENDIX B

Variation of Temperature with Time at Different Air Flow Rate

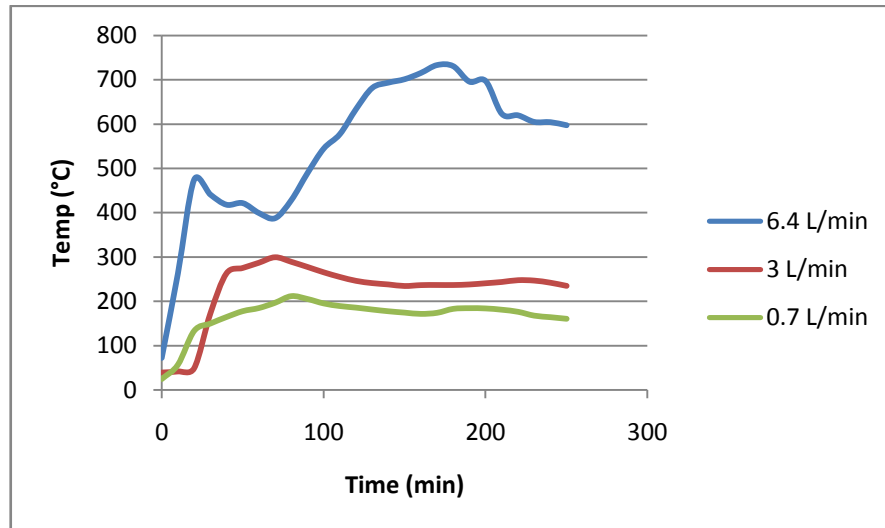


Figure B 1: Variation of Temperature with Time at Different Air Flow Rate

APPENDIX C

MATLAB Simulation Codes

Function file

```
function f=Modelling(X)

C=37.5482; H=4.607; O =37.67; N=0.46; S=0.012;

%x, y, and z = numbers of atoms of hydrogen, oxygen, and nitrogen per
one atom of carbon in the feedstock
x=1.47;
y=0.75;
z=0.01;

% Molar mass of biomass
M_bm=1*12+x*1+y*16+z*14;

% Moisture content
MC = 0.0988;

% Molar mass of water
M_w = 18;

% w amount of water one kmol of feedstock
w=(M_bm*MC) / (M_w*(1-MC) );

% Enthalpy kJ/kmol
CH4_H298=-74.8e3;

CO_H298=-110.5e3;

CO2_H298=-393.5e3;

H2OV_H298=-241.8e3;

HV_H2O= 44000; %kJ/ Kmol

% Estimation of lower heating value for biomass in(kJ/kg)
LHV_kg=4.187*(81*C+300*H-26*(O-S)-6*(9*H+MC) );

% Estimation of lower heating value for biomass in(kJ/kmol)
LHV=LHV_kg*M_bm;

%Products of complete combustion of biomass (kmol)
P_comb=CO2_H298*1+(x/2)*H2OV_H298;

% Enthalpy of biomass kJ/kmol
delH_bio=LHV+P_comb; %kJ/kmol;

%delH_bio=-2.2319e+005;%-2.2183e+005
T0=298;
```

```

T=773;

%coefficients of specific heat capacity for various gases
c1_N2=28.90;    c2_N2=-0.1571e-2;    c3_N2=0.8081e-5;    c4_N2=-
2.873e-9;

c1_CO2=22.26;    c2_CO2=5.981e-2;    c3_CO2=-3.501e-5;    c4_CO2=-
7.469e-9;

c1_H2=29.1;    c2_H2=-1.92e-3;    c3_H2=4.00e-6;    c4_H2=-
8.70e-10;

c1_CO=28.16;    c2_CO=0.1675e-2;    c3_CO=0.5372e-5;    c4_CO=-
2.222e-9;

c1_CH4=19.9;    c2_CH4=5.21e-2;    c3_CH4=1.269e-5;    c4_CH4=-1.13e-
8;

c1_H2O=32.2;    c2_H2O=1.92e-3;    c3_H2O=1.06e-5;    c4_H2O=-
3.60e-9;

%specific heat capacity of individual kJ/kmol.k
delH_CO=c1_CO*(T-T0) + (c2_CO/2)*(T^2-T0^2) + (c3_CO/3)*(T^3-T0^3) + ...
(c4_CO/4)*(T^4-T0^4) + CO_H298;

delH_H2 =c1_H2*(T-T0) + (c2_H2/2)*(T^2-T0^2) + (c3_H2/3)*(T^3-T0^3) + ...
(c4_H2/4)*(T^4-T0^4);

delH_CO2=c1_CO2*(T-T0) + (c2_CO2/2)*(T^2-T0^2) + (c3_CO2/3)*(T^3-T0^3) +
...
(c4_CO2/4)*(T^4-T0^4) + CO2_H298;

delH_CH4=c1_CH4*(T-T0) + (c2_CH4/2)*(T^2-T0^2) + (c3_CH4/3)*(T^3-T0^3) +
...
(c4_CH4/4)*(T^4-T0^4) + CH4_H298;

delH_H2OV =c1_H2O*(T-T0) + (c2_H2O/2)*(T^2-T0^2) + (c3_H2O/3)*(T^3-T0^3) +
...
(c4_H2O/4)*(T^4-T0^4) + H2OV_H298;

delH_N2=c1_N2*(T-T0) + (c2_N2/2)*(T^2-T0^2) + (c3_N2/3)*(T^3-T0^3) + ...
(c4_N2/4)*(T^4-T0^4);

delH_H2OL= HV_H2O;

A=delH_H2 - delH_H2OV - ((z/2+3.76)/2)*delH_N2;

B=delH_CO + 2*delH_H2OV - delH_CH4 + ((z/2+3.76)/2)*3*delH_N2;

C=delH_CO2 + 2*delH_H2OV - delH_CH4 + ((z/2+3.76)/2)*4*delH_N2;

D=delH_H2OV - delH_H2OL;

```

```

E= delH_CH4 + (x/2 -2)*delH_H2OV + ((z/2+3.76)/2)*(x/2 -2-y)*delH_N2 -
delH_bio;

K1 = exp((7082.848/T) + ((-6.567)*log(T))+ ((7.466e-3*T)/2) - ((2.167e-
6*T^2)/6) + (0.701e-5/(2*T^2)+ 32.541));

K2=exp((4276/T)-3.961);

X1=X(1);
X2=X(2);
X3=X(3);

f(1)= X1^2*K1 + X2 + X3 - 1;

f(2)=-K2*X1*X2 + ( w - 1.26)*K2*X2 + 2*K2*X2^2 - X1*X3 + 2*K2*X2*X3;

f(3)=A*X1 + B*X2 + C*X3 + D*w + E;

X5 = X(1)^2*K1;

X4 = -X(1) + 2*X(2) + 3*X(3) + w + x/2 -2;

m = 0.5*(-X(1) + 3*X(2) + 4 *X(3) +(x/2 -2-y));

X6 = (z/2 + m)*3.76;

V(1)=(X1/(X1+ X2+ X3+ X5 + X6))*100;

V(2)=(X2/(X1+ X2+ X3+ X5 + X6))*100;

V(3)=(X3/(X1+ X2+ X3+ X5 + X6)*100);

V(5)=(X5/(X1+ X2+ X3+ X5+ X6)*100);

V(6)=(X6/(X1+ X2+ X3+ X5+ X6)*100);

disp(X(1:3)')
disp(X5')
disp(X6')
disp(V(1:3)')
disp(V(5)')
disp(V(6)')
disp(m')

```

Call file

```

clc
clearall
X0=[0.6 0.6 0.3];

options = optimset('Display', 'iter', 'MaxFunEvals',1000);
[X, fval, exitflag, output] = fsolve('Modelling',X0, options);

```

MATLAB Simulation Results

The results were gotten by changing the gasification temperature in the MATLAB code

Table C1: MATLAB Simulation Results

Temperature (°C)	500	600	700	800	900	1000	1100
H ₂	15.45	18.56	18.44	16.68	14.47	12.22	10.10
CO	14.11	16.99	18.31	18.72	18.65	18.22	17.50
CO ₂	21.48	16.55	14.14	13.05	12.54	12.33	12.36
CH ₄	10.46	3.99	1.27	0.39	0.13	0.05	0.02
N ₂	38.50	43.91	47.84	51.14	54.22	57.18	60.02
m	0.2174	0.3061	0.3724	0.4178	0.4555	0.492	0.5293
Calorific Value (MJ/m ³)	7.63	5.91	5.04	4.57	4.21	3.87	3.52

APPENDIX D

Variation of Syngas Composition with Time at Various Oxygen Enrichment

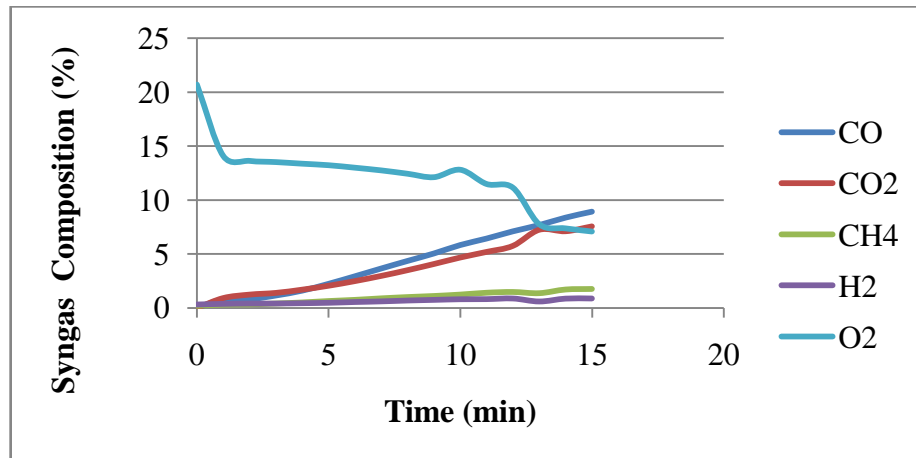


Figure D 1: Variation of Syngas Composition with Time at 30% Oxygen- Enriched Air (10 L/min) Rice Husk Gasification

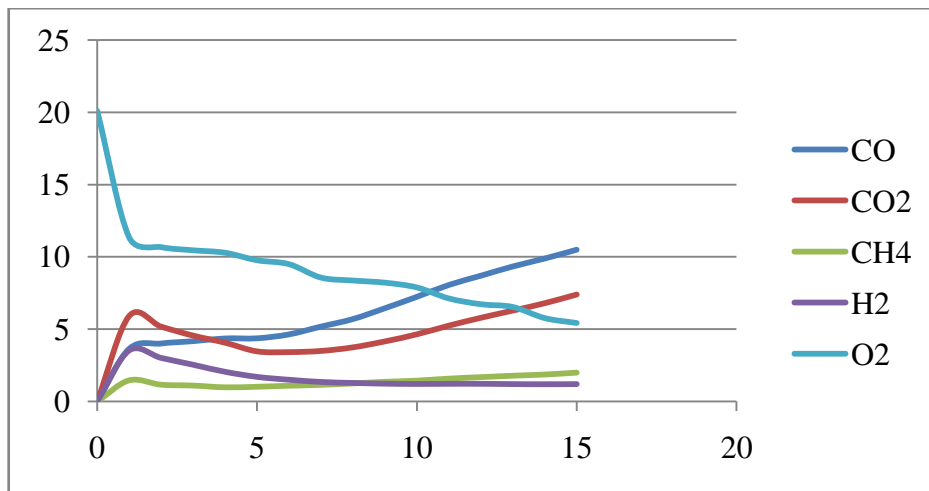


Figure D 2: Variation of Syngas Composition with Time at 40% Oxygen- Enriched Air (10 L/min) Rice Husk Gasification

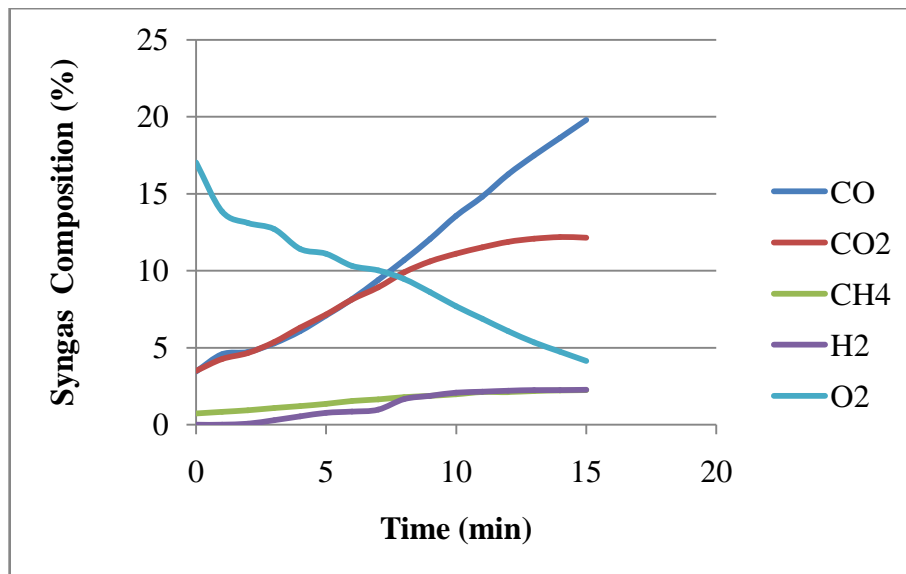


Figure D 3: Variation of Syngas Composition with Time at 50% Oxygen- Enriched Air (10 L/min) Rice Husk Gasification

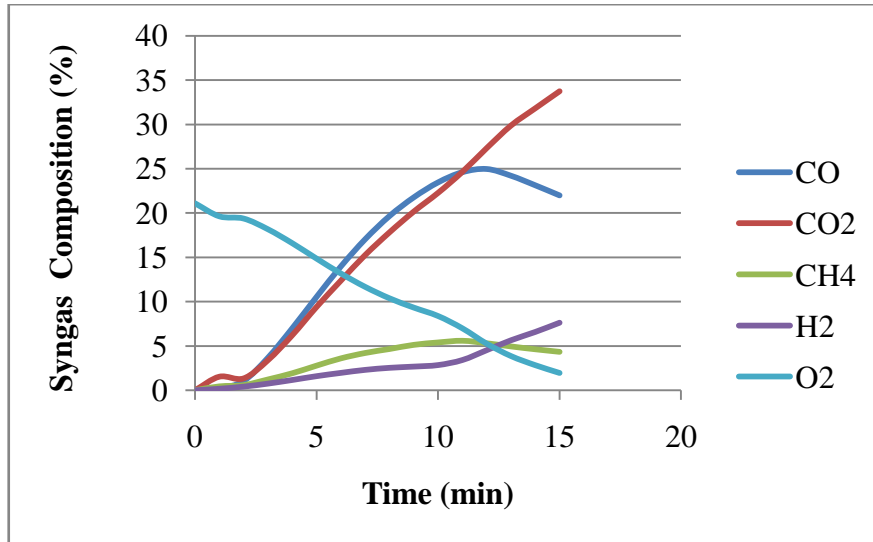


Figure D 4: Variation of Syngas Composition with Time at 60% Oxygen- Enriched Air (10 L/min) Rice Husk Gasification

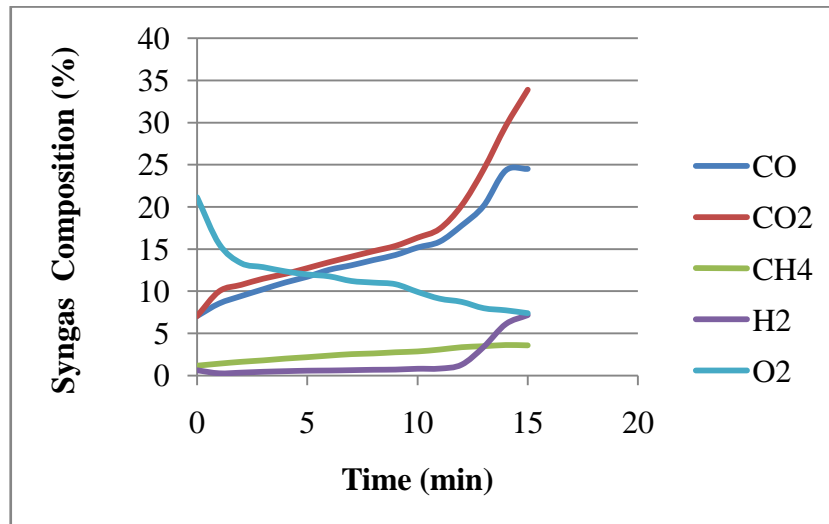


Figure D 5: Variation of Syngas Composition with Time at 80% Oxygen- Enriched Air (10 L/min) Rice Husk Gasification

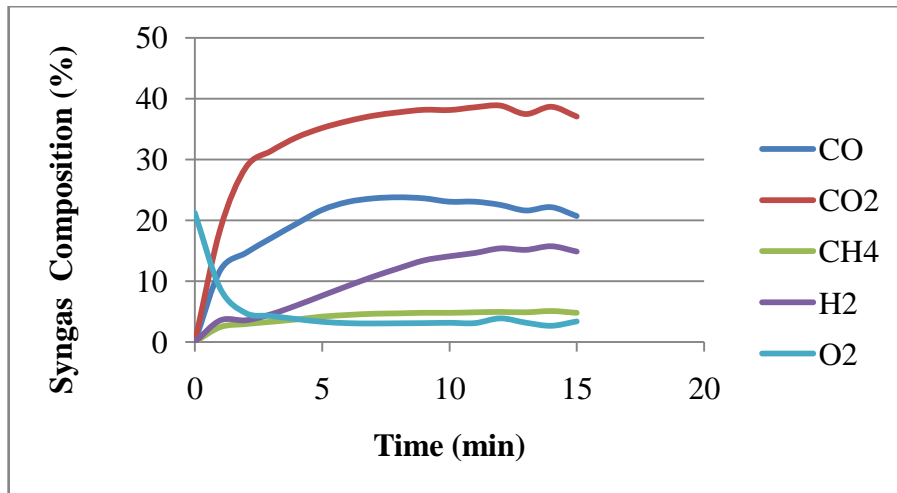


Figure D 6: Variation of Syngas Composition with Time at 100% Oxygen-Enriched Air (10 L/min) Rice Husk Gasification

APPENDIX E

Stoichiometric Amount of Oxygen and Equivalence Ratio Calculation.

For Air (21 % O₂ and 79% N₂),

Stoichiometric Amount = $[0.1153C + 0.3434(H - O/8) + 0.0434S]$ kg/kg dry fuel
(Basu, 2010)

$$= 4.393 \text{ Kg air/Kg dry rice husk}$$

Equivalence ratio for gasification using Air at 6.4 L/min = 0.384 m³/hr

Feed consumption rate measured = 0.807 Kg/hr

Density of air @ 25 °C = 1.1860 Kg/m³

Actual air required for gasification = Mass flow rate of air / Feed consumption rate

$$\begin{aligned} \text{Mass flow rate of air} &= 0.384 \text{ m}^3/\text{hr} \times 1.1860 \text{ Kg/m}^3 \\ &= 0.455 \text{ Kg/hr} \end{aligned}$$

Equivalence ratio = Actual air required for gasification / Stoichiometric Amount

$$\begin{aligned} &= 0.455 / 0.807 / 4.395 \\ &= 0.128 \end{aligned}$$

For air enrichment 30% (30 % O₂ and 70% N₂),

Stoichiometric Amount: 1 mole of N₂ per O₂ required 30/70 = 2.33 moles

Total mole of 30% oxygen enrichment = 3.33 mole

1 kg of O₂ required 28/32 x 3.33 = 2.91 Kg air

4.166 Kg O₂ stoichiometric Amount of air @ (21 % O₂ and 79% N₂) is 4.393 Kg air/Kg dry rice husk, therefore 2.19 Kg O₂ required Kg required 3.067 Kg air/Kg dry rice husk.

Equivalence ratio at (30 % O₂ and 70% N₂) at 10 l/min (0.6 m³/hr).

Density of oxygen @ 25 °C = 1.3087 = 1.1860 Kg/m³

Density of air oxygen enrichment = 0.3 x 1.3087 + 0.7 x 1.145 = 1.19411 Kg/m³

$$\begin{aligned} \text{Mass flow rate of air} &= 0.6 \text{ m}^3/\text{hr} \times 1.19411 \text{ Kg/m}^3 \\ &= 0.716 \text{ Kg/hr} \end{aligned}$$

$$\begin{aligned} \text{Equivalence ratio} &= \text{Actual air required for gasification}/\text{Stoichiometric Amount} \\ &= 0.716/0.807/3.067 \\ &= 0.289 \end{aligned}$$

Similarly calculation was for other oxygen enrichment with theirs results in Table E 1

Table E1: Stoichiometric Amount of air and Equivalence ratio at 40% to 100% Oxygen Enrichment

Oxygen enrichment	Stoichiometric Amount (Kg air/Kg dry rice husk)	Equivalence ratio
40%	2.301	0.391
50%	1.845	0.494
60%	1.583	0.601
80%	1.153	0.823
100%	1.054	0.955