EXPERIMENTAL STUDY OF BIOMASS GASIFIACTION IN A DOWNDRAFT GASIFIER USING DIFFERENT FEEDSTOCKS

By

Henok Mekonnen

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Abstract

The primary interest of this research work is to study the gasification properties of different biomass feedstock materials which are easily available in Ethiopia. An overview of biomass is discussed in this paper so as to have a clue what chemical composition does a biomass material can have and its implication of energy conversion. The different types of conversion processes are also covered in order to show the possible ways that energy can be extracted from biomass and to compare their merits and demerits relative to gasification. A precise theoretical overview of gasification is dealt which has laid a very starting ground for what is done in the simulation and experimental works.

Experimental investigation is an irreplaceable tool to get a very meaningful finding in this research even though simulation can give a good guidance and a pre insight. Simulation work alone can be misleading since many simplifying assumptions were taken in order to make it possible to simulate the very complicated thermo-chemical process inside the gasifier and also the still unclearly phenomenon of tar formation. Both simulation and experimental work are undertaken in this research. A Matlab program is used to simulate the effects of moisture content and equivalence ratio on the constituent gas composition of the produced gas. An algorithm based on a thermodynamic model with certain simplifying assumptions is used so that the Matlab program will not miss the physical outlook of the modeled gasification process. Tables and figures are generated which are suitable to see the effects of different parameters on the final output of the gasification process.

An experimental investigation is undertaken using different feedstock materials. The experiments are being carried out for some selected biomass materials which are charcoal, sawdust, coffee husk and a mixture of sawdust and coffee husk. The effects of moisture content and equivalence ratio on the final syngas composition are studied. The amount and nature of tar produced while gasifying the different feedstock is also examined. A comparison of the simulation and experimental works is done and it was reasoned out what effects the deviation of the experimental result from that of the simulation work. It was also attempted to compare the simulation and experimental results with those in literatures. At the end recommendations and suggestion of future works are presented concerning the work of this research.

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Nomenclatures

a – g	Coefficient for Gibbs free energy empirical relation
C, H, O, N, S	Carbon, hydrogen, oxygen, nitrogen and sulfur fraction in biomass (dry basis)
C*, H*, O*	Carbon, hydrogen and oxygen fraction in biomass (wet basis)
C_{px}	Specific heat capacity of X species (kJ/kmol)
$c_1 - c_4$	Coefficient for specific heat capacity
ΔG_T	Gibbs free energy (kJ/kmol)
$\Delta g_{f,T,i}$	Change in Gibbs free energy for individual gas with temperature
HHV	Higher Heating Value (MJ/kg)
H_{bio}	Heat of formation (kJ/kmol)
H_f^0	Enthalpy of formation (kJ/kmol)
k_1	Equilibrium constant for water gas shift reaction
k_2	Equilibrium constant for $C + 2H_2 \rightarrow CH_4$
LHV	Lower heating Value (MJ/kg)
M_{bio}	Molecular weight of biomass
m	Moisture content in biomass (% dry basis)
m_w	Number of moles of water vapor (dry basis)
n_i	Number of moles of species i
n_{tot}	Total number of gaseous moles in the reactor
P_X	Partial pressure of species of X inside the reactor
p_i	Products of complete combustion of biomass (kmol) for species i

w	Stoichiometric coefficients of water vapor
x, y, z	Normalized coefficient of atomic hydrogen, oxygen and nitrogen for biomass molecule
$x_1 - x_5$	Number of moles of H_2, CO, CO_2, H_2O, CH_4 respectively
x_g	Number of moles of oxygen for gasification

Table of Contents

List of tables

List of Figures

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND

Today's world is facing a serious problem related to energy and environment. Every living thing is entirely dependent on and affected by energy and its impact, respectively. Particularly, human beings are able to manipulate energy into their day to day activity. Due to the rapid growth of world's population, and vast and rapid human activities as a result of technological development, modernization and competition, today's world energy demand is extremely high. As a result, fossil fuels which have been utilized for many centuries are getting rapidly depleted, while their price is drastically escalating to a level which worsens the world's unstable and unjustified economy, particularly the poor countries like Ethiopia.

Another equally important and related issue to be addressed is environmental concern. Planet earth is simply reacting for the aggressive effects of dangerous gaseous emissions, which are the byproducts of combustion of fossil fuels, which is too loud to be unnoticed. However, still there is hope to be in a position to guarantee the supply of the present and future energy demand and preserve the world with its natural environment, but to do so engineers need a mind equipped with sustainability and environmentalism.

Among the most common sources of energy which are distinguished as renewable, biomass is a very well known candidate, which is to be treated in this research. It has been utilized even by earliest ancestors, but not in smart and efficient way. Nowadays, the growth of science and technology has brought many innovative mechanisms to use these energy sources in an efficient and manageable way. There are well developed thermo-chemical and bio-chemical conversion practices to extract energy from biomass materials. Direct combustion, gasification and liquefaction are the possible thermo-chemical conversion methods whereas anaerobic digestion (biogas), fermentation and extraction rely on biochemical conversion of biomass materials.

Gasification is a thermo-chemical conversion process in which dry or liquid biomass is converted into a gaseous fuel (synthetic gas or syngas). This process is accomplished through devices called gasifiers. Updraft, downdraft, fluidized bed and entrained bed are the various conventional types of gasifiers with different designs. Gasification involves four major sub-processes: Drying, Pyrolysis, Combustion and Reduction, which are undertaken in the respective zones of the gasification unit. In the drying zone, the water within the fuel is removed by evaporation at about 200 ^{0}C, and the volatile gases are released from the dry fuel through thermal degradation in the pyrolysis stage at a temperature between 400 ^{0}C - 600 ^{0}C **[1]**. Following pyrolysis, the gas and char are totally or partially combusted to provide the energy required in the other steps, where the temperature reaches up to 1350 ^{0}C in this combustion zone. Finally, the remaining char is reduced with CO_2, H_2O and heat to form H_2 and CO **[1]**.

The gas produced as a result of the gasification process is a mixture of combustible and non-combustible components and it has a higher energy value than the solid biomass. The combustible gases are H_2, CO and several hydrocarbons, and the non-combustible gases are CO_2 and N_2. Depending on the content of N_2 in the fuel and on the gasification process, ammonia (NH_3) will as well be part of the product gas, which is a potential source of NO_x emission.

The useful energy that can be extracted as a result of biomass gasification greatly depends on the type of biomass material used and to some considerable extent on how efficiently the gasification process is undergone. Biomass contains carbon, hydrogen, oxygen, moisture and small amounts of sulfur and nitrogen. Among those constituent elements, carbon, hydrogen and sulfur are the combustible elements which are burned and release energy during combustion. Since those combustible elements have their own unique heating values, the compositional difference between the various biomass materials results in the difference between their heating values. In a broader sense, the composition of combustible elements, ash and moisture content are the important parameters to be dealt with, whenever gasification is of interest. Therefore, a clear and sufficient knowledge of gasification properties of various feedstocks is crucial for an effective design of biomass gasification system. A thorough experimental investigation is a powerful and overtopping tool to carry out such a task involving a precise study of advanced thermo-chemical and thermo-physical processes.

1.2. OBJECTIVE

The general objective of this research is to undertake an experimental study of the gasification properties of various biomass feedstocks and present figures of important parameters. In addition to the experimental task modeling of the gasification processes backed with reasonable assumptions will be one important part of this thesis work.

The specific objectives of this research are:

- To identify the promising biomass materials for gasification which are available in Ethiopia.
- To evaluate the biomass gasification properties of those identified biomass feedstock materials.
- To develop a good computational model of the gasification process.
- To analyze the experimental results, compare with and validate the modeled results, and suggest the best and suitable application of the corresponding studied biomass materials.

1.3. PROBLEM STATEMENT

- Energy and environment are two different entities but never treated separately, particularly in today's world's condition. The issues like the rapid reduction in amount and increase in price of non-renewable energy sources together with their disastrous and fatal environmental consequences are the foremost engineering and social problems.
- Ethiopia is very poor while it has surplus natural resources. Particularly, its renewable energy potential exceeds far more than its energy demand. Biomass alone would have contributed a substantial share of the total fuel consumption of the country, if it was exploited and utilized properly. Only through the stream of gasification, there exist a wide range of applications. The synthetic gas can be utilized directly for heating or can also be applied to power a gas turbine for electricity production or acts as a fuel for a gas engine, with additional mechanism for gas cleaning supplemented. More advanced processes like steam reforming and water-gas shift reaction would make it possible methanol and hydrogen synthesis, which in turn can be utilized for fuel cells and automobile engines. However, still each year a worth of millions of dollars are being expended for purchasing oil from oil selling countries. It has three significant impacts:
    - The money spent for purchasing oil covers a substantial share of the country's annual budget due to the fast growing oil price, its extensive use for many applications ranging from household, then automobiles and aircrafts, up to energy

  intensive big industries. In addition the additional transportation and taxation costs are too significant to be neglected.
  - It creates extreme shortage of the country's foreign currency (especially USD), which in turn, critically affects the foreign exchange power of the country.
  - Obviously, it has a negative environmental impact, since the combustion of fossil fuels is highly responsible for the emission of pollutant gases.
- There is no efficient biomass utilization trend in Ethiopia. As a result, a huge extent of the biomass energy is lost due to incomplete combustion and wasted heat. Besides, wood is almost the only biomass energy source that has been sacrificed for many years without any significant use of alternative biomass resources. It has been extensively used for covering house hold energy demand and for charcoal production, particularly in the rural areas where much of the country's population belong to. This, together with rapid population growth and urbanization, result in deforestation in the past years.

1.4. RESEARCH METHODS

1. Literature review
   - Literatures are reviewed so as to get a firm theoretical ground and learn about many of the previously undertaken related works so as to use them as guidance and see gaps out of them.
2. Theoretical approach
   - Modeling of the gasification process will be undertaken so as to lay ground for the experimental study and to compare the actual condition relative to the modeled one, in order to evaluate the efficiency of the gasification process.
3. Experiment
   - Independent experimental study of various selected biomass feedstock materials.
   - Equipments to be used:
     - Gas analyzer
     - Thermocouples
     - Pressure gauge
     - Flow meter
4. Analyzing and interpreting the results.

5. Drawing relevant figures of important parameters from experimental records for various types of biomass feedstock, making validation of the modeled and experimental results to each other and with other literatures.

1.5. CONCEPTUAL DESIGN

A commercial downdraft gasifier with a model - BECE-HK15 is a prime unit of the experimental setup which is placed in AAiT Mechanical Engineering workshop. Usually, the direction of flow of both the fuel and the gas is downward unlike updraft gasifier, which in turn results in very low tar content but relatively higher cost of auxiliary fuel. The gasification system consists of the reactor (the gasifier itself), and auxiliary components as an air supply fan, ash removal system, gas cleaning units and different gauges.

Temperatures in the gasifier’s combustion zone, reduction, pyroysis zone and drying zone are acquired by inserting thermocouples into the respective zones. In the combustor’s outlet, syngas temperature is measured by the appropriate thermocouple and syngas composition is measured by a gas analyzer. A serious of batch experiments will be carried out and the acquired data will be collected and prepared for analysis and interpretation.

CHAPTER TWO

LITERATURE REVIEW

2.1. BIOMASS AND CONVERSION TECHNOLOGIES

The renewable nature of biomass makes any research undertaken on energy extraction and utilization from biomass either by gasification or other alternative mechanisms to be viable without any doubt. This is primarily because the world has learned the unreliability and harsh environmental impact of the fossil fuels for the past decades and tends to turn its face to the alternative renewable energy sources. The reason that biomass did not buy much attention and had not been for widespread use is that it has low energy density and fossil fuels were formerly cheap and are easily suited for many applications in process and transport industries. However, the fossil fuels, ones the world had trusted and made widespread use of it are now getting depleted and putting planet earth on an extremely complicated energy and environmental crisis.

It is repeatedly reported by many that biomass gasification is very suitable for decentralized energy supply in developing countries **[2]**. For a country like Ethiopia, there is a vast portion of the nation's population living without electricity. One feasible solution to such a nation is to use biomass as an energy source through gasification for applications of water pumping for irrigation and household use and also electric generation driven by biomass gasification. Another interesting fact that needs to be mentioned is that any organic waste can be potentially a source of biomass energy. As a result, wastes from some industries are very suitable for biomass gasification. In the case of sugar cane industry, wherever in the world and even in Ethiopia, the well known waste product of it called baggase, can be a very good candidate for biomass gasification. It can either be directly used for thermal application (heating) or electricity generation through gasification which saves a great deal of energy and also enhances the waste recycling process of the plant.

Biomass literally means any material that is organic. The principal sources of biomass energy are the phototropic organisms or plants. Photosynthesis is the fundamental process responsible for the building up of the energy contained in biomass materials. After all, the sun is the ultimate source of energy for planet earth and solar energy is the one that drives the endothermic reaction of photosynthesis. Biomass by its nature has low energy density relative to the conventional (fossil) fuels, but, despite this fact it is found almost everywhere in the world unlike the fossil fuels, which are extremely limited to few and specific locations of the planet.

2.1.1. Biomass Overview

Matter that constitutes of the part of diversified nature on earth which is composed of organic material is called Biomass. The sun is the ultimate source of energy contained in every biomass material. The energy flow goes from the primary source–the Sun to the Autotrophs, then to the Hetrotrophs, through photosynthesis and respiration, respectively.

> *Autotrophs are organisms that are capable of synthesizing organic molecules from inorganic materials through photosynthesis, in which sunlight is used as the only source of energy to drive the endothermic reaction occurring in photosynthesis.*
>
> *Hetrotrophs are organisms that feed on or consume autotrophs or other hetrotrophs, and utilize the biochemical energy that was primarily stored in autotrophs, in their daily activities through respiration.*

Photosynthesis: $6\ CO_2 + 6\ H_2O + \text{light} + \text{chlorophyll} \rightarrow C_6H_{12}O_6$ (glucose) + $6\ O_2$

$\Delta G = 480$ KJ/mol

Respiration: $C_6H_{12}O_6 \rightarrow 6\ CO_2 + 6\ H_2O$

Autotrophic organisms (plants) are major constituents of the total biomass whereas wastes from animals and algae contribute the remaining share. The main elemental components that build up a biomass material are carbon, hydrogen, oxygen and nitrogen. Nutrients like phosphorous, potassium, sulfur, sodium, magnesium, calcium, etc…, are minor constituents in a generic biomass. Heavy metals like iron, cobalt, copper, zinc, etc… can also be found in some cases **[3]**.

What are the polymers found in plants?

*A plant cell contains the polysaccharides: cellulose, hemicelluloses, and lignin, very carbonaceous molecules. The cell wall of a plant cell is primarily built up of cellulose with the elemental formula $(C_6H_{10}O_5)_n$ where lignin acts as bounds in the cell **[3]**.*

A representative chemical composition of any biomass material can therefore be approximated and takes the form $CH_xO_yN_z$, encompassing only the major elements inside the biomass, which is sufficient enough for energy analysis alone. The variable subscripts represent the proportion of each element depending on the compositional nature of a specific biomass material. The combustible elements are only carbon, hydrogen, and sulfur among the constituent elements. Nitrogen is incombustible unless at very high temperatures and oxygen is simply an agent of the combustion process. Apart from those chemically bound ones, nitrogen and oxygen are introduced together with the combustion air.

Biomass, as it is known is also a source of food for non-producer living things on earth, particularly humans. There appears a food- energy dilemma in some circumstances while using some virgin biomass that could potentially be a source of food. So it is highly recommended to use waste biomass for energy extraction than virgin biomass.

> ***Virgin Biomass****: biomass material which is unexploited biomass as it is grown in nature. Wood, corn pops, cereals, etc are some examples of virgin biomass.*
>
> ***Waste Biomass****: is a biomass that is partially or totally exploited and discarded as a waste. Coffee husk, wood chips, sewage sludge, rice husk are a few examples of waste biomass.*

The most important properties of a biomass are chemical composition, moisture content and ash content. Ash is an inorganic material, which binds inside the organic matter of the biomass material, and is highly associated with the oxygen, sulfur and nitrogen containing functional groups. Someone can’t help the chemical composition of the biomass but it is possible to go through pre-treatment processes to upgrade the quality of the biomass by dealing with its moisture content, density and particle size, through physical pre-treatment processes. The common physical pre-treatment processes are:

- Dewatering
- Drying
- Size reduction
- Densification and
- Separation

2.1.1.1 Dewatering and Drying

An enormous amount of energy is sacrificed to release the moisture that binds in a biomass material, prior to that it starts to deliver a net energy output. In other words, when biomass with too much moisture gets gasified, large share of its energy will be employed to drive off the water and no net useful energy will be left. Therefore, it is a must to go through drying process to achieve considerable reduction of the moisture content. Basically, there are two types of moisture removal techniques known as dewatering and drying.

Dewatering: refers to the removal of all or part of the contained moisture from biomass as a liquid. It involves open air storage, filters, screening devices, centrifuges, hydro cyclones and expression processes. The major drawback of this process is that it can disturb the cell wall structure which leads to carbon losses which in turn degrades the calorific value of the biomass material.

Drying: Unlike dewatering the moisture leaves the biomass material as a form of vapor in drying process. It has a wider option of mechanisms as compared to dewatering. The most common approaches of biomass drying are:

- **Open air solar drying**
  This approach can be regarded as a traditional way of drying and in fact the most cost effective process. It can be effective if moisture content up to 35 % is desirable **[5]**. The disadvantages are: it is a very slow process, local climate dependent, semi labor intensive and worst of all it may decompose if care should not be taken.
- **Batch drying, Kiln drying**
  The very interesting feature of this process is that the hot synthetic gas or the combusted flue gas can be used to yield the required amount of heat enough to dry the wet biomass. In this approach drying up to 15% moisture by weight of the biomass is attainable **[3]**.
- **Continuous drying by stack gases**
  Hot air or stack gases are made to contact biomass material as it enters the combustion space, usually in a countercurrent fashion. The positive feature of this process is its ease of operation being continuous but only a limited amount of moisture can be removed. A simple formula can be helpful to estimate the rate of moisture removal.

$WG = 2940\ M/(T_i - T_o)$, where

$T_i = temperature\ of\ drying\ gas\ entering,$ ℃

$T_o = temperature\ of\ drying\ gas\ leaving,$ ℃

$M = water\ evaporated\ (kg/h)$

$WG = drying\ gas\ weight\ (kg/h)$

2.1.1.2 Torrefaction

Oxygen is inherent in biomass materials which contributes nothing to the heating value of the biomass. Surely, it will improve the energy density of the biomass material if this inherent oxygen is totally eliminated. Torrefaction is the process of effectively lowering the O/C of the biomass. The thermo-chemical process of torrefaction is an interaction of drying process and an incomplete pyrolysis process, and is characterized by the following parameters **[1]**.

- Reacting temperatures between 200 and 300 ℃
- Heating rate less than 50 ℃$/min$
- Absence of oxygen
- Residence time 30 minutes at temperature above 200 ℃
- Ambient pressure
- Flexible feedstock

2.1.1.3. Size Reduction

Many biomass materials are available in irregular shapes and uneven size composition of granules. A well prepared biomass to be the right size with even particle size distribution has got very important property in a biomass energy conversion process. In addition, the right size and shape for the optimum ratio of surface to volume of gasifier space occupied gives the highest attainable heat transfer rate. In fact, the optimum size characteristics of the particle for biomass energy conversion, is determined by the following reactor parameters **[3]**.

- Reactor design
- Operating conditions (significantly temperature)
- The feeding mechanism and with least importance the ash removal

Size reduction can be undertaken by cutting, chipping, grinding or steam explosion technology, while it depends on the type of biomass and reactor to decide which size reduction process should be applied. Steam explosion is the treatment of the wood chips with steam at elevated pressure and temperature for short period of time followed by rapid decomposition. Apart from the alteration of the physical state of the wood structure chemical changes of hemicelluloses and lignin may occur **[3]**.

2.1.1.4. Densification

Densification of biomass is a process of reducing the bulk volume of the material by mechanical means for easy handling, transportation and storage. It actually is a further treatment after dealing with size reduction of the biomass particle. Pelletization is the typical type of densification process. Mechanical extrusion of biomass through a cylindrical passage gives off equal size, dense pellets with similar moisture content. Apart from ease of handling and storage densification has other outstanding advantages like high energy density, improves biomass stability and facilitates the feeding of biomass to reactors. Above all, there should be a balance between the cost of biomass pre-treatment and the incremental improvement in conversion efficiency.

2.1.2. Conversion Technologies

Conversion processes in biomass can be employed in different ways. The most common and matured techniques are:

- Physical conversion
    - Pressing
- Thermal conversion
    - Pyrolysis
- Biochemical conversion
    - Fermentation
    - Biomass digestion
- Thermo-chemical conversion
    - Gasification (discussed in later topics)

2.1.2.1. Pyrolysis

Pyrolysis is a direct thermal decomposition of organic compounds in the absence of oxygen without any chemical process. Volatile gases escape within some temperature range that is enough to effect thermal degradation of the bonding between the molecules. The remaining matter after pyrolyzing of the biomass material is a solid residue called coke containing fixed carbon, ash and liquid tar. The major constituents of the volatile matter are hydrogen, carbon monoxide and methane, whereas a small amount of some light hydrocarbons are released apart from the condensable tar. Some heavy hydrocarbon tars are condensable at normal condition and leave as liquid during pyrolysis process. Mostly pyrolysis is considered to be endothermic, but the direction of energy flow is reversed at higher temperatures. Temperature between 400 ℃ and 450 ℃ is taken as the range of typical temperatures in which pyrolysis usually occurs, and most probably proceeds being endothermic within this temperature range **[1]**. The kinetics of pyrolysis can be expressed by the governing equation,

$$\frac{-dm_v}{dt} = Aexp(-E/RT)(1-m_v) \ ,$$

Where, $m_v = mass\ of\ volatiles\ remaining$

$A = Arrhenius\ constant$

$E = Activation\ energy\ (KJ/Kmol)$

$R = Universal\ gas\ constant\ (KJ/KmolK)$

$T = Temperature\ (K)$

2.1.2.2. Pressing

Some biomass materials only need physical applications in order to extract more versatile fuel in a liquid form. Many vegetable oils contain polyglycerides which can serve as a diesel substitute after treatment. Two methods are commonly employed in this technique:

Cold pressing*: is the easiest technique in which oil is extracted by only applying pressure at normal condition. The latter treatment is only filtration.*

***Warm pressing**: is applied after heating in order to loosen the molecular bond. Organic solvents are then added to extract the polyglyceride molecules, and then avoid themselves by further purification.*

2.1.2.3. Fermentation

Fermentation is a natural process initiated by microorganisms of the saccharomyzes type, similar to common yeast cultures and ethanol is the end product. Hexose and Pentose sugars ferment readily, i.e. being oxidized while excess electrons are transferred to organic acceptor molecules instead of to oxygen. The process is actually anaerobic. Some microorganisms could operate also in aerobic condition (in air) but would not produce any ethanol. Thus, ethanol is produced when growth parameters do not support an oxidative metabolic process, thereby requiring a less efficient life cycle resulting in ethanol as a waste product.

Polymers found in biomass materials usually found in complex form like starch in sugar cane and potato. So, this complex glucose polymer (starch) should be first broken into simpler sugars, maltose and glucose, before fermentation can start. Ethanol is the final byproduct mixed with small amounts of methanol, or higher alcohols and diluted in water. Finally the ethanol is separated from the water through distillation. Ethanol can potentially be extracted from:

- Agricultural crops: cereals, maize, potato which are starch containing
- Cellulose and its derivatives: Acid hydrolysis or enzymatic hydrolysis is the pretreatment that precede the fermentation process. Liquefaction and saccharification of cellulose into C5-C6 sugars can also be applied before fermentation.

2.1.2.4. Biogas Digestion

Biogas digestion is a very common biomass conversion process which can be implemented with least complication in design and operation than any other conversion process. In is anaerobic process driven by naturally occurring microorganisms in which organic molecules contained in biomass materials are broken down into simpler and more important molecules. A simplified stoichiometry for anaerobic digestion of biomass is given by:

$C_6H_{10}O_5 + H_2O \rightarrow 3\ CH_4 + 3\ CO_2$

Biogas digestion is fully accomplished through the following four important steps:

Hydrolysis: Polymers such as cellulose, starch, proteins and lipids are hydrolyzed to soluble compounds.

Fermentation: Soluble compounds are converted to different compounds such as amino acids, fatty acids, alcohols, CO_2, H_2, NH_3, and H_2S.

Acetogenesis: Fermentation products are then converted to a mixture of hydrogen, low molecular weight acids (primarily acetic acid) and carbon dioxide.

Methanogenesis: products of the acetogenesis steps are reacted together to produce methane.

The first three steps of anaerobic digestion are relatively rapid, while the methanogenesis step is a slow and more sensitive process. Compared to thermal processes, the residence time of biomass material in a digester is relatively long, seconds versus weeks. Optimal condition for methanogene bacteria is essential for a good proceeding of anaerobic digestion. The activity of methanogene bacteria is the highest within two temperature ranges: 30–40 ℃ (mesophilic condition) and 50–70 ℃ (thermophilic condition) **[3]**. Other important process conditions are, among others, a neutral PH (6.5-8), and low concentration of ammonia and heavy metals **[3]**.

Waste biomass like cattle manure, fish waste, fat waste, grass, and food waste can be directly employed for the production of biogas. Biogas primarily consists of methane (60-65%) and the rest is CO_2, but still there are traces of H_2S, NH_3 and some other organics that give bad odor. It is estimated that around 50-60% of the initial energy content in the organic material found in biomass can be converted to biogas in a properly operated digester **[3]**.

2.2. GASIFICATION

Biomass gasification is an incomplete combustion of biomass resulting in production of combustible gases consisting of carbon monoxide (CO), hydrogen (H_2) and traces of methane (CH_4). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and ignition), can be used as substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol- an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. Since any biomass can undergo gasification, this process is much more attractive than ethanol production or biogas where only few selected biomass materials can produce the fuel.

Besides, there is a problem that solid wastes are seldom in a form that can be utilized economically, e.g. wood wastes can be used in hog fuel boiler but the equipment is expensive and energy intensive and energy recovery is low. As a result it is often advantageous to convert this waste into more readily usable fuel form like producer gas. Hence the attractiveness of gasification.

2.2.1. Historical Background

The history of use of biomass as a source of energy in general is traced back to the day that human beings started using fire to cook their food and warm their body and near surrounding. However, gasification technology is believed to be emerged about 180 years ago in Europe **[1]**. It was the times which people had not make use of fossil fuels as energy source. It was biomass which had served as the only and primary source of energy that could be utilized by combustion, for so many years before the discovery of fossil fuels. A dramatic shift was happened in the energy scenario when fossil fuels were begun to be exploited and processed to a very versatile, high energy density and cheap energy source for widespread applications ranging from household use to automotives and even driving industries at different level and power plants. It is obvious that many of the steam power plants around the world are still powered by coal. In fact, biomass gasification had gotten the chance to develop until the emergence of the fossil based fuels. It is estimated that there were about 9,000,000 vehicles in Europe, which were driven by engines powered by producer gas, in 1945 just after the end of the Second World War **[1]**. Due to the stability and economic reforms after the First World War in Europe and other parts of the world, opportunities were created for the discovery and exploitation of fossil fuels. Another incidence (WWII) came that made the use of gasification to re-emerge after once the world was introduced to the high quality but environmentally unfriendly energy source-the fossil fuels. The notable reason was that there appeared a great difficulty in accessing resources which made the nations being incapable to buy fossil based fuels as easily as they did before. Even though gasification had been extensively used during and a bit longer after WWII, interest had soon declined over it and left the energy era to fossil based fuels, which have been dominantly utilized throughout the world since then, even have become one important factor in determining the Worlds' economy. This unevenly distributed gift of nature made some lucky nations to collect enormous treasure out of it. But, nowadays, many researchers and government bodies in different countries, particularly in Europe are giving attention, indeed making efforts on developing and utilizing the potential locked inside the art of gasification. Sweden is the notable country together with some other European countries in spreading the use of gasification and many renewable energy alternatives, as a whole **[1]**.

2.2.2. Theory of Gasification

Gasification is an advanced thermo-chemical conversion process in which solid and in some cases semi-solid biomass is converted to a more versatile gaseous fuel through successive thermal and chemical activities undertaken inside the controlled environment of the gasifier. The gaseous fuel produced as a result of gasification is termed as producer gas or synthetic gas, sometimes syngas. The chemical composition of the gas varies depending on the feedstock nature, the type of gasifier used and other parameters which have their own effect during the gasification process. Despite the somehow differences due to the above mentioned reasons, the syngas is composed mainly of CO, CO_2, H_2, H_2O and a small amount of methane (CH_4).

2.2.2.1. Process Zones

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are:-

Drying Zone: Is the zone in which the moisture inside the fuel is released at about temperatures between 200 and 300 ^{0}C **[1]**.

Pyrolysis Zone: In this stage tar and other volatiles are driven off. The temperature in this region is between 400 and 500 ^{0}C **[1]**.

Combustion zone: It is the region near around the air supply nozzle in which partial combustion of the biomass is undertaken. The temperature here can reach up to 1000 ^{0}C and above and is the maximum out of the gasification zones inside the reactor **[1]**.

Reduction Zone: It is the last stage and important reduction reactions are undertaken here.

Though there is a considerable overlap of the processes, each can be assumed to occupy a separate zone where fundamentally different chemical and thermal reactions take place.

2.2.2.2. Reaction Chemistry

Gasification, being an advanced thermo-chemical reaction, it involves different reactions that are undertaken successively or simultaneously. The following reactions take place in combustion and reduction zones.

Combustion Zone

The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and carbon monoxide is obtained from the incomplete combustion. Water is also produced from the hydrogen inherently found in the biomass. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450 ^{0}C **[1]**. The main reactions, therefore, are **[4]**:

Oxidation: $C + O_2 \leftrightarrow CO_2$, $\Delta H = -393.5\ KJ/mol$

Partial Oxidation: $C + \frac{1}{2}O_2 \leftrightarrow CO$, $\Delta H = -110.5\ KJ/mol$, and

$2H_2 + O_2 \leftrightarrow 2H_2O,\ \Delta H = -242\ KJ/mol$

Reduction Zone

The products of partial combustion (water, carbon dioxide and uncombusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place **[4]**.

Main Reduction reactions: $C + CO_2 \leftrightarrow 2CO$, $\Delta H = 172.4\ KJ/mol$

$$C + H_2O \leftrightarrow H_2 + CO\ , \Delta H = 131.3\ KJ/mol$$

Methanation reactions: $C + 2H_2 \leftrightarrow CH_4$, $\Delta H = -78.4\ KJ/mol$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O\ , \Delta H = 206.1\ KJ/mol$$

Product gas from biomass gasification needs to be enriched with hydrogen to the required molar ratio H_2/CO for the methanation reaction to proceed. This is done by the water-gas-shift reaction, where a certain part of the CO in the product gas is sacrificed to produce H_2.

Water-gas-shift reaction: $C + H_2O \leftrightarrow CO_2 + H_2$, $\Delta H = -41.1\ KJ/mol$ **[5]**

Another very important reaction can be involved by technically introducing steam into the gasification medium. It is called steam- methane reforming, which is advantageous if hydrogen production is of primary interest.

Steam- methane reforming: $CH_4 + H_2O \leftrightarrow CO + 3H_2$, $\Delta H = -206.1\ KJ/mol$ **[5]**

The main reduction reactions, being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the reduction zones are normally between 800 and 1000 ^{0}C **[6]**.

Pyrolysis Zone

Pyrolysis is an intricate process that is still not completely understood. The products depend upon temperature, pressure, residence time and heat losses. However, following general remarks can be made about them.

Up to the temperature of 200 ^{0}C only water is driven off. Between 200 ^{0}C and 280 ^{0}C, carbon dioxide, acetic acid and water are given off. The real pyrolysis, which takes place between 280 to 500 ^{0}C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed. Between 500 to 700 ^{0}C the gas production is small and contains hydrogen **[7]**.

Thus, it is easy to see that updraft gasifier will produce much more tar than downdraft one. In downdraft gasifier the tars have to go through combustion and reduction zones, results in decomposition of light tars.

2.2.2.3. Types of Gasifiers

There are different types of gasifiers used depending on factors like the type of biomass used, moisture content, syngas end use application, desired total gasification efficiency and other parameters including economic factor. The major categories in gasifier types are mostly based on the way in which the feedstock moves inside the reactor. They are broadly classified as **[8]**:

- Quasi non-moving or self-moving feedstock
- Mechanically moved feedstock
    - Downdraft gasifier

  - Updraft gasifier
  - Cross-draft gasifier
- Fluidized feedstock
  - Bubbling bed (BB) gasifier
  - Circulating fluidized bed (CFB) gasifier
  - Entrained-bed gasifier
- Special reactors
  - Spouted bed gasifier
  - Cyclone gasifier

The most common types of gasifiers among the above listed ones are, downdraft gasifier, updraft gasifier, bubbling bed and circulating fluidized bed gasifiers, which are to be discussed in this paper. Bubbling bed and Circulating fluidized bed gasifiers are discussed in a single section as fluidized gasifiers due to minor differences between them.

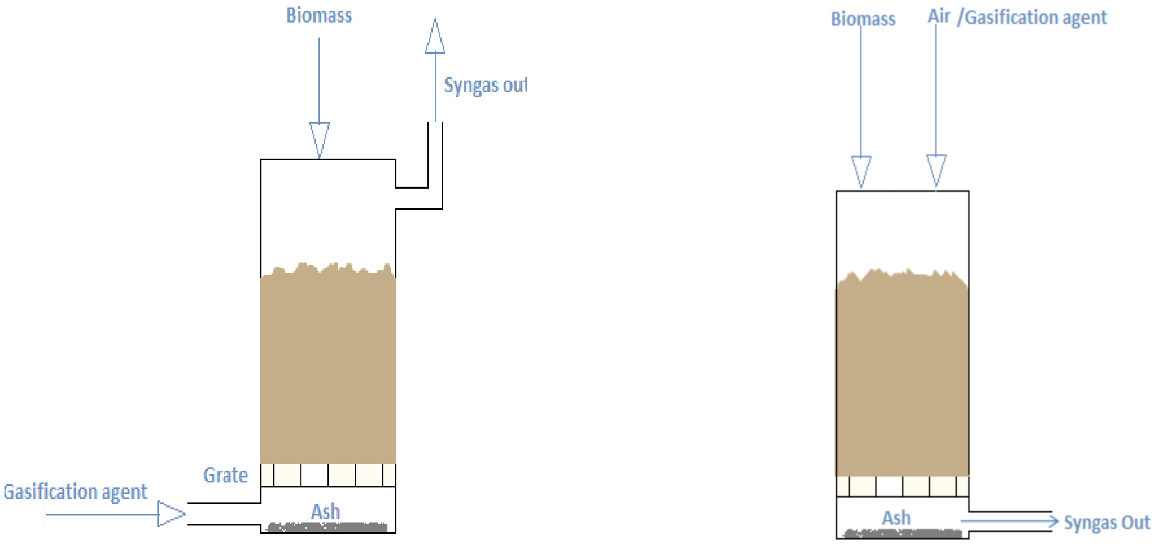


Figure 2-1 : - An Updraft (left) and a Downdraft (right) gasifiers

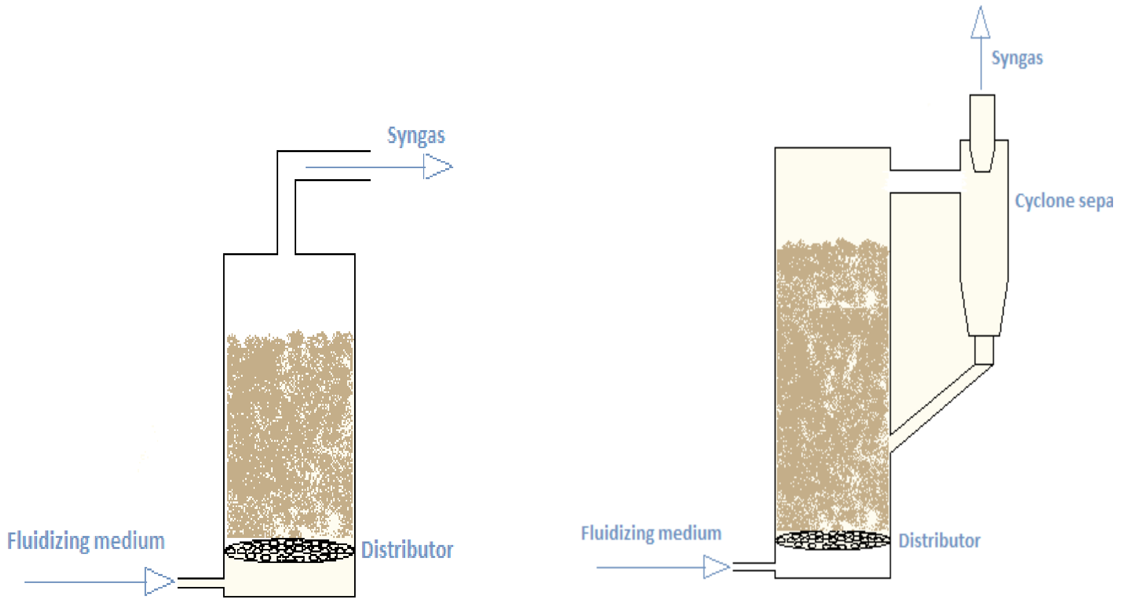


Figure 2-2 : - A Bubbling bed (left) and a Fluidized bed (right) gasifiers

Updraft Gasifier

The movement of the feedstock and the gasifying agent are in opposite directions in this kind of gasifier (also called counter current gasifier). Since syngas formed is not forced to pass through the hot high temperature zone, the tar content is high in the syngas from this gasifier. On the other hand, the temperature of syngas exiting from this gasifier is lower around (200 to 300 ^{0}C) and hence the thermal efficiency of this kind of gasifier is high **[9]**. Due to high tar content in the syngas, a subsequent tar cleaning system is needed, which can become a major investment if the end process requires tar-free syngas.

Downdraft Gasifier

In a downdraft gasifier, the feedstock and gasifying agent both move in the same direction. The gases have to pass through the high temperature so amount of tar is significantly lower than that in an updraft gasifier. The particulate content is however higher for downdraft gasifier and the thermal efficiency is lower since syngas draws an appreciable amount of energy while passing the high temperature zone inside the gasifier.

Fluidized Gasifier

In fluidized bed gasifier, feedstock is fluidized with some bed material like sand/silica with gasifying medium which can be air or steam. Fluidized bed gasifier can further be classified into two types: bubbling bed and circulating fluidized bed. Circulating fluidized bed adds one more feature to bubbling bed such that solid material trapped in the gas phase is trapped and re-circulated back to the gasification bed. This provides the significant advantages over the bubbling bed gasifier in terms of mass conversion efficiency and reduces particulate content in the syngas output.

Table 2-1 :- The advantages and disadvantages of various types of gasifiers [8]

Characteristics	Gasifier Type			
	Downdraft	Updraft	Bubbling Bed	Circulating Bed
Gasifier Size	Higher space requirement for higher throughput due to modular design of the gasifier and high residence time		Less space required due to enhanced heat transfer resulting in much faster gasification and lower residence time inside the gasifier	
Temperature Profile	Not uniform temperature distribution in the radial direction		Uniform temperature distribution inside the gasifier	
Permissible particle size/ Size sensitivity	Less than 50 mm (good)		Less than 5mm (more sensitive to particle size)	
Reaction zone temperature	800- 1100 ^{0}C		800- 1000 ^{0}C	
Ability to handle fine particles	Limited		Good	
Moisture content	Very flexible	Flexible	Flexible	
Gas exit temperature	600- 800 ^{0}C	250 ^{0}C	850 ^{0}C	
Tar Concentration	Very low (0.01-6 gm/ Nm^{3})	Very high (50 gm/ Nm^{3})	6- 12 gm/ Nm^{3}	
Carbon conversion	Very good		Fair	Very good

efficiency				
Thermal efficiency	Very good	Excellent	Good	Very good
LHV of syngas	Poor		Poor	Fair
Cold gas efficiency	Above 80 %		Above 90 %	
Gas clean up	High cleaning required	Relatively clean gas	Clean up required for dust and tar	
Dust content in syngas	High	Low	Higher dust content	
Energy requirement for operation	Low		High due to requirement of fans for fluidization	
Investment	Higher investment for energy generation compared to BBG/CFBG (for large scale output)		Lower investment	
Process control	Cannot be controlled effectively as BBG/CFBG		Easy process control	
Applications	Small to medium scales		Large scales	

2.2.3. Gasifier Fuel Characterization

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with some range of stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated and fuel processing done.

Many gasifier manufacturers claim that a gasifier is available which can gasify any type of fuel. There is no such thing as a universal gasifier. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round.

Thus a gasifier fuel can be classified as good or bad according to the following parameters **[3]**:

- Energy content of the fuel
- Bulk density
- Moisture content
- Dust content

- Tar content
- Ash and slagging characteristics

Energy content and bulk density

The energy content of a biomass is determined by its nature of elemental composition where as it is possible to change the bulk density of a biomass material with physical pre-treatment processes like densification. Literatures are available on the calorific values of various common types of biomass if not bomb calorie meter is not used to determine it experimentally.

Moisture content

In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pretreatment of fuel is required. Generally, desirable moisture content for fuel should be less than 20 % **[10]**.

Dust Content

All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2-6 gm/m^3 of dust **[11]**. The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

Tar Content

Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60 % water) to black and highly viscous (7 % water) **[12]**. There are approximately 200 chemical constituents that have been identified in tar so far **[12]**.

Very little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 gm/m^3 of tar. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers. However because of localized inefficient processes taking place in the throat of downdraft gasifier it does not allow the complete dissociation of tar **[12]**. More research effort is therefore needed in exploring the mechanism of tar breakdown in downdraft gasifiers.

Ash and Slagging Characteristics

The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition have a major impact on trouble free operation of gasifier. Ash basically interferes with gasification process in two ways:

- It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed
- 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.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier. Slagging, however, can be overcome by two types of operation of gasifier:

- Low temperature operation that keeps the temperature well below the flow temperature of the ash.
- High temperature operation that keeps the temperature above the melting point of ash.

The first method is usually accomplished by steam or water injection while the latter method requires provisions for tapping the molten slag out of the oxidation zone. Each method has its advantages and depends on specific fuel and gasifier design.

2.3. RELATED WORKS

One strong parameter in biomass gasification is moisture content. In almost all literatures the effect of moisture content is studied by varying it within some reasonable range. It in fact, strongly depends on the type of gasifier used. Updraft gasifiers can work with relatively higher moisture content than other types like down draft gasifiers. This is because; in updraft gasifier the flow of gas and feedstock is in a counter current arrangement, which allows the moisture in the biomass to be released when the hot producer gas passes through in the opposite direction. Pratik N. Sheth **[13]** presented that the upper limit of acceptable moisture content for a downdraft gasifier is 40 % on a dry basis. Z. A. Zainal **[14]** has also studied the effect of moisture content by varying from 0 % to 40% on a wet basis, while wood chip was used as a feedstock. Pratik N. Sheth **[13]** showed that moisture content critically affects the fuel feed rate. When the moisture content increases the fuel feed rate decreases while keeping other parameters constant. This is due to the fact that more energy is spent in the drying zone to eliminate the large amount of moisture, which in turn retards the biomass pyrolysis. In the study of ZA. Zainal, it is clearly shown that CO_2 and H_2 increase, whereas CO decreases with increase in moisture content. However, no significant change was experienced regarding the amount of CH_4 and N_2 produced **[14]**.

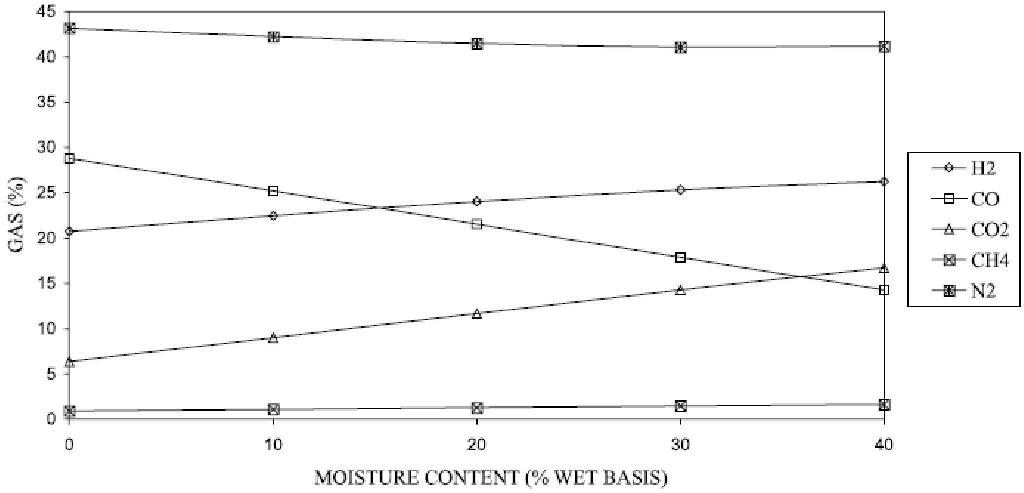


Figure 2-3 : - Effect of moisture content in the wood chips on gas composition at 800 ^{0}C [14]

Since the heating value of the producer gas is one of the most important desired parameters, the compositional nature of the gas should as much favor as possible to yield the highest calorific value of the producer gas. Therefore, there should be an optimum moisture content, at which the amount of CO and H_2 compromised.

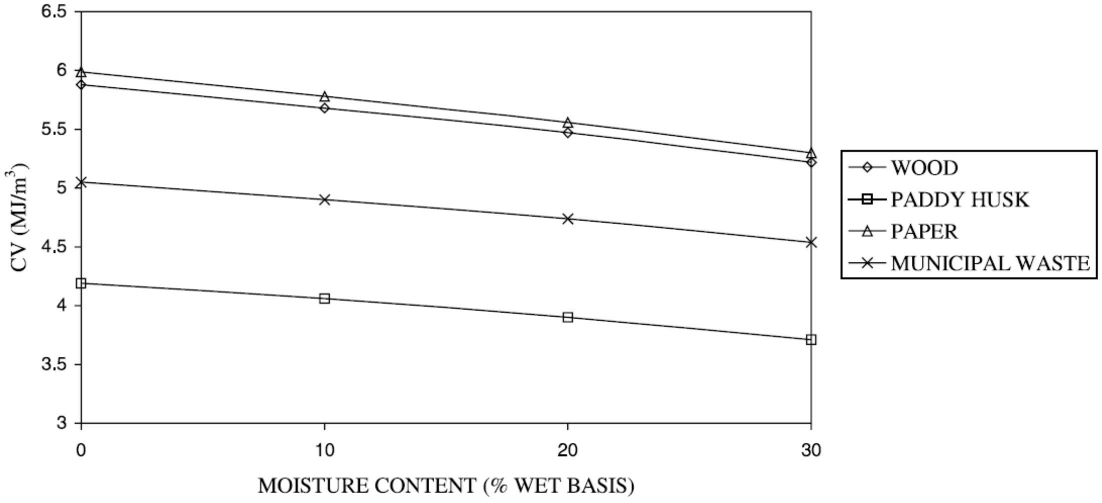


Figure 2-4 : - Calorific value against moisture content at 800 0C for different biomass materials [14]

Hydrogen production is enhanced by increase in moisture content and the rise of temperature, through steam reforming and water gas shift reaction. But, too much moisture decreases the temperature and negatively affects the production of hydrogen. So to take advantage of the moisture content without severely affecting the gasification temperature, steam is intentionally introduced inside the gasifier, which greatly aids the steam reforming and water gas shift reactions. But still it will get bad if the amount of steam to be introduced into the gasifier is not optimized with the amount of biomass. On an experimental study on biomass air steam gasification, done by P.M.Lv, steam was made to vary from 0 to 1.8 kg/h, while keeping other conditions constant **[15]**. A similar trend is observed here too, in which, H_2 and CO_2 tends to increase with increase in steam to biomass ratio (S/B) while CO decreases with increase in steam to biomass ratio. But most importantly, there is a critical point of S/B, below which the gas yield, LHV and carbon conversion efficiency exhibit an increasing trend and a decreasing trend above this line. The increasing trend in the first range is because steam introduction helps water-gas shift reaction, steam reforming and methanation reaction, which in turn increases the production of H_2, CH_4 and other light hydrocarbons. On the contrary, the latter decreasing trend above the optimum S/B ratio (which is 1.35 in this article) was arisen from a lowered reaction temperature as a result of excessive quantity of low temperature steam **[15]**.

Gasification is simply a thermo-chemical conversion of raw biomass materials into gaseous fuel. It differs from a direct combustion in a way that it is undertaken in a controlled environment, in which drying, pyrolysis, partial oxidation and reduction reactions are the major processes occurring in the different zones of the gasifier, while only a limited amount of air is supplied so , interdependent. As a result, the appropriate amount of air that is needed to be supplied depends on the type of feedstock used, the moisture content, size, type of gasifier and soon. However, the solo effect of the equivalence ratio on the overall performance of the gasification process can be studied by keeping other parameters constant. Without experimental proof, one with a basic knowledge of combustion chemistry can suggest that, as the amount of air supply increases the rate of combustion does so. This implies that as the equivalence ratio increases, the rate of biomass consumption increases, which in turn increases the rate of gas production. A work that strongly support the above statement is clearly presented by Pratik N. Sheth **[13]**, where the gas production rate per unit weight of biomass increases with an increase in equivalence ratio significantly, in almost a linear fashion. It can also be said that ER is a dominantly decisive parameter that determines the biomass feed rate and gas production rate. In this paper figures showing the effect of ER on producer gas composition, temperatures at different zones of the gasifier and calorific value of the producer gas are presented. A very similar trend is observed on the effect of ER on CO and CO_2, between this paper and that of P.M.Lv **[15]**.

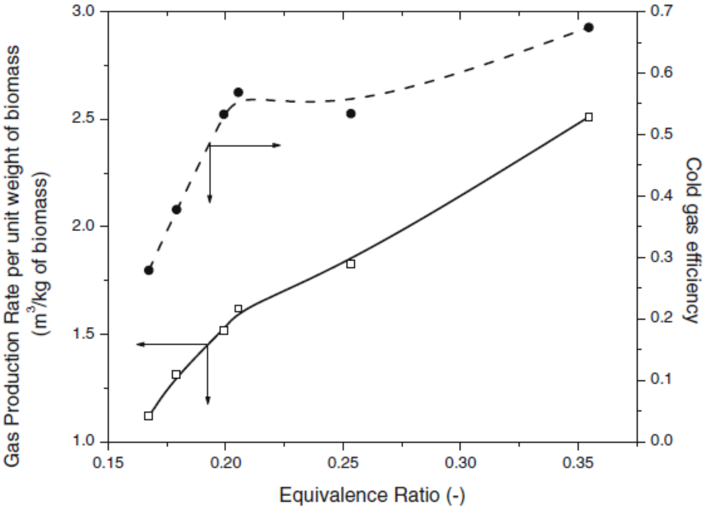


Figure 2-5 : - Effect of equivalence ratio on producer gas production rate per unit weight of biomass and cold gas efficiency [13]

When ER increases the molar fraction of CO_2 decreases until it starts to increase when it reaches some point where ER becomes 0.205 in the former one and 0.23 in the latter one, whereas CO is observed to have an increasing and decreasing trend that looks very nearly a mirror image of that of CO_2. A slight difference between the above referred literatures is noticed on their report about the fraction of H_2 in the producer gas. Pratik N. Sheth reported that H_2 has a similar trend to that of CO while the other said there is only a slight variation in the fraction of H_2 as a result of variation in equivalence ratio.

Nitrogen is a very dominant constituent in air. As a result, it is obvious that the fraction of nitrogen as well increases in the synthetic gas composition as the equivalence ratio increases. This in fact, is witnessed by the work of Pratik N. Sheth **[13]**. Based on this report, the reduction of LHV of the syngas after some value of equivalence ratio is due to that, the increased level of nitrogen concentration dilutes the fraction of other important gases like CO and H_2.

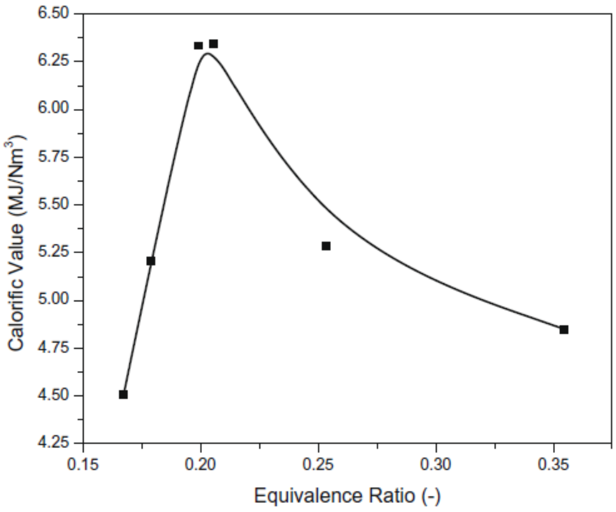


Figure 2-6 : - Effect of equivalence ratio on calorific value of producer gas [13]

This paper also mentioned that the enhanced oxidation as a result of variation in equivalence ratio is one important reason for increasing and decreasing of the LHV of the syngas before and after the optimum equivalence ratio, respectively. In addition, when more nitrogen is introduced into the gasifier with air, it then left the gasifier capturing some amount of heat, which again reduces the temperatures in the different zones of the gasifier **[13]**.

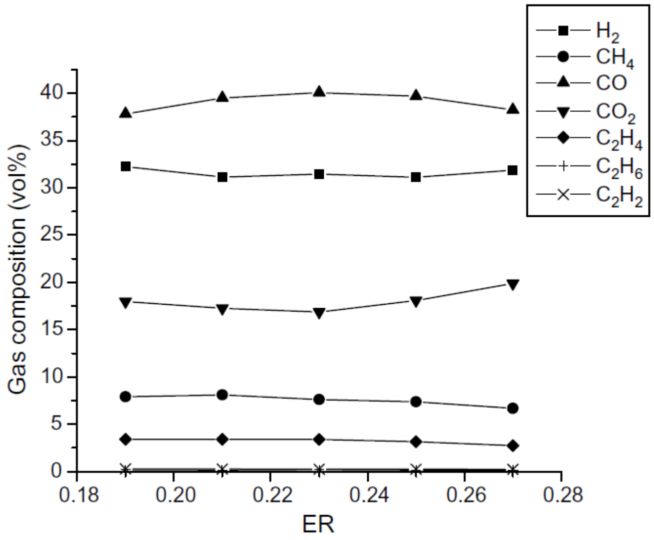


Figure 2-7 : Effect of ER on gas composition with biomass feed rate: 0.512 kg/h; temperature: 800 ^{0}C; steam rate; 0.8 kg/h [15]

A terrible headache in gasification is the formation of tar during the pyrolysis stage. Tar removal is one of the foremost interest in designing of gasifiers and while carrying out related researches. Gas cleaning systems ranging from simple arrangement and equipment design to very complicated ones are involved in order to overcome the potential danger of tar formation.

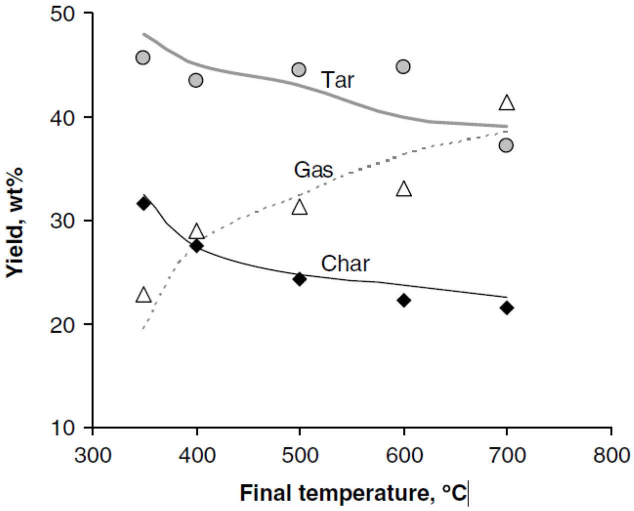


Figure 2-8 : The variations of % gas, char and tar yield with final temperature of gasifier [16]

It is known that the formation of tar is greatly influenced by the temperature inside the gasifier and also by the equivalence ratio. Yao Bin Yang **[16]** has shown the variation of % tar yield with respect to the gasifier final temperature for various feedstocks. As the final temperature increases the tar formation was observed to lower, which is because of the enhanced tar cracking process as a result of elevated temperature. In addition to that temperature favors tar cracking, catalytic action are also known to be involved in tar cracking. Potassium acts as a catalyst which can be found in many biomass materials **[16]**.

The effect of equivalence ratio on tar cracking has been studied by Thana Phuphuakrat **[17]**. Equivalence ratio and gasification temperature go in parallel, since the former favors the latter. As a result, as the equivalence ratio increases tar formation reduces. But during this study **[17]** it was observed that heavy tar showed an increase with equivalence ratio, whereas light tar decreased, and the total tar yield decreased as well with equivalence ratio. This is a good indication of that tar yield cannot be totally eliminated by just parameterization. This calls for a need to accompany effective gas cleaning system. Thana Phuphuakrat **[17]** has made a thorough investigation on the tar removal efficiency of different equipments in a gas cleaning line. The venturi scrubbers and saw dust adsorbers are the gas cleaning units which are evaluated based on their efficiency in tar removal, in this article. Approximately 47 – 74 % of the total tar mass could be removed by the venturi scrubbers, whereas the tar removal efficiencies of the serious saw dust adsorbers were found to be between 4 and 68 %, compared to the outlet tar concentration of the scrubbers. Light aromatic hydrocarbon tar are non-condensable at the ambient temperature and can safely burn in internal combustion engines, which are the major tar components detected at the exit of the gas cleaning system, as Thana reported **[17]**.

CHAPTER THREE

EQUILIBRIUM MODELLING

The product gas as a result of biomass gasification is a mixture of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), water (H_2O) and nitrogen if air is used as a gasifying agent. Despite the presence of the above mentioned chemical elements in every product gas from various biomass materials their compositional proportion greatly varies from one biomass material to another. In addition to the nature of the biomass used, the working condition of the gasification reactor, pre-treatment measures and some intentionally applied techniques will also have a considerable contribution for the quality and chemical composition of the producer gas. An exhaustive literature is already present for biomass gasification using various common and appropriate feedstocks. But, most of the time, syngas composition is unknown until the gasification work is conducted. On the other side, experimental work is often resource intensive (time and money) and a mathematical model predicting syngas composition (concentration of H_2, CO, CH_4 and CO_2) using elemental analysis of biomass would be helpful. There are several models such as thermodynamic equilibrium, kinetics-free, steady-state, semi-transient and transient that can be used to determine the syngas composition. Among these techniques, the thermodynamic equilibrium model is the simplest of all types and gives syngas composition for various biomass types at selected gasification temperatures with reasonable accuracy.

A system is said to be in thermodynamic equilibrium when it is in thermal, mechanical and chemical equilibrium. Chemical equilibrium is the state of minimum Gibbs free energy and maximum system entropy. Mechanical equilibrium occurs when the system is not performing or receiving any work. Thermodynamic equilibrium provides a closer prediction when the reaction temperature is sufficiently higher. Equilibrium conditions are difficult to achieve in practical operating conditions and results obtained from thermodynamic equilibrium modeling can serve as the maximum limit on syngas composition. The objective of this chapter is to develop a mathematical expression to determine syngas composition based on carbon, hydrogen and oxygen that can be applicable to any biomass type. In addition, the analysis also includes the effect of moisture content in biomass.

3.1. MODEL FORMULATION

Empirical relations were developed for predicting the individual fraction of major combustible species of the syngas, CO and H_2. Although these equations can be used for any type of gasifier, it is more accurate for a downdraft gasifier due to its low tar content. Although there are several factors affecting syngas composition from biomass, it mainly depends on the gasifier type, feedstock and feedstock pre-treatment, gasifying medium and operating parameters such as temperature, pressure and equivalence ratio. In this study the formulation of the thermodynamic model was based on the following assumptions:

- All carbon content in biomass is converted into gaseous form and the resident time is high enough to achieve thermodynamic equilibrium. This might not be true in an actual gasification process; however the degree of error introduced by this assumption is acceptable and the applicability of this assumption is confirmed in many literatures. The products taken into account are CO, CO_2, H_2, CH_4, N_2 and water. These are the major gaseous compounds formed during the gasification process. Hydrocarbons other than CH_4 were assumed negligible in syngas and were not taken into account.
- Ash in the feedstock was assumed inert in all gasification reactions although it holds true typically for reaction temperatures less than 700 ^{0}C whereas gasification generally occurs at temperatures higher than 700 ^{0}C. Therefore, the relations derived in this study cannot be used effectively for biomass with high mineral content.
- All the gaseous products are assumed to behave as ideal gases. This will lead to insignificant error because the gasification in downdraft gasifiers is conducted at high temperature and low pressure. Also, the pressure drop inside the gasifier was assumed to be negligible.
- The reaction was auto-thermal and no external source of heat was supplied. The process is completely adiabatic so that no heat losses occur from the gasifier.
- The amount of tar in syngas was assumed to be negligible. This places the restriction upon the use of this model for various configurations of gasifier design. For downdraft gasifier, this assumption is valid since the tar concentration is significantly low compared to other configurations. For an updraft gasifier, where the higher hydrocarbons produced are not cracked and hence contain high fraction of tar, the results of this modeling cannot

be applied. Modifications such as subtracting the amount of volatiles from the biomass and treating the rest as char for the gasification can be done to improve the model. However, this will lead to increasing amount of error in terms of the final results. Output from the gasification was assumed only to be permanent gases free of oxygen which is true because the oxygen supplied is far less than the needed for combustion in a gasification process. Sulfur and Chlorine content were also neglected since they are less than 0.6 % in most biomass feedstocks.

The chemical composition of biomass was taken to be in the form $CH_xO_yN_z$ and the gasification reaction can be written in the following form:

$$CH_xO_yN_z + m_wH_2O + x_g(O_2 + 3.76N_2) \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4H_2O + x_5CH_4 + \left(\frac{z}{2} + x_g3.76\right)N_2 \quad (1)$$

Where m_w can be calculated using the following relation.

$$m_w = \frac{(M_{bio}m)}{18(1-m)} \quad (2)$$

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

$$C + CO_2 \rightarrow 2CO \quad (3)$$

$$C + H_2O \rightarrow CO + H_2 \quad (4)$$

The two reactions shown above can be combined into one single reaction known as water-gas shift reaction.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (5)$$

The other reaction that is prominent in the gasification process is formation of methane as shown below:

$$C + 2H_2 \rightarrow CH_4 \quad (6)$$

The water-gas shift and methanation reactions are the two major reactions that occur in the gasification process. The equilibrium constant for these two above equations as the function of their molar composition can be written as follows:

$$k_1 = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} \tag{7}$$

$$k_2 = \frac{P_{CH_4}}{(P_{H_2})^2} \tag{8}$$

Gibbs free energy is used in determining the value of k_1 and k_2 as presented in the equation below. For the given ideal gas, the Gibbs free energy is a strong function of the reaction temperature and a weak function of pressure.

$$\ln K(T) = \frac{-\Delta G_T}{RT} \tag{9}$$

$$\Delta G_T = \sum_i x_i \Delta \bar{g}^0_{f,T,i} \tag{10}$$

Where $\Delta \bar{g}^0_{f,T,i}$ is empirically calculated according to the equation below:

$$\Delta \bar{g}^0_{f,T,i} = \Delta \bar{H}^0_{f,i} - aT \ln T - bT^2 - \frac{c}{2}T^3 - \frac{d}{3}T^4 + \frac{e}{2T} + f + gT \tag{11}$$

The carbon, hydrogen and oxygen balance of the reactions taking place in the gasification give:

$$x_1 + x_3 + x_5 = 1 \tag{12}$$

$$x + 2m_w = 2x_2 + 2x_4 + 4x_5 \tag{13}$$

$$y + m_w + 2x_g = x_1 + 2x_3 + x_4 \tag{14}$$

Now, there are five equations and six unknowns. The final equation was obtained by an enthalpy balance inside the gasifier. Total enthalpy content in any chemical species is the sum of its chemical enthalpy and sensible enthalpy and can be written as follows:

$$\begin{aligned}&H^0_{f-biomass} + m_w\left(H^0_{fH_2O} + H_{vap}\right) + x_g\left(H^0_{fO_2} + 3.76H^0_{fN_2}\right) = x_1\left(H^0_{fCO} + \int_{298}^{T_g} C_{PCO}dT\right) + \\ &x_2\left(H^0_{fH_2} + \int_{298}^{T_g} C_{PH_2}dT\right) + x_3\left(H^0_{fCO_2} + \int_{298}^{T_g} C_{PCO_2}dT\right) + x_4\left(H^0_{fH_2O} + \int_{298}^{T_g} C_{PH_2O}dT\right) + \\ &x_5\left(H^0_{fCH_4} + \int_{298}^{T_g} C_{PCH_4}dT\right) + \left(\frac{z}{2} + x_g 3.76\right)\int_{298}^{T_g} C_{PN_2}dT\end{aligned} \qquad (15)$$

In this paper LHV is used for evaluating heat of formation of biomass. The equation used to calculate the heat of formation of biomass is shown below:

$$H^0_{f,bio} = LHV + \sum_{i=1}^{n} n_i p_i \qquad (16)$$

LHV is calculated in dry basis of biomass and was calculated using the following equation:

$$LHV = 4.187\big(81C + 300H - 26(O - S) - 6(9H + m)\big)(kJ/kg) \qquad (17)$$

The total enthalpy equation can be reduced to the following form since $H^0_{fN_2}$, $H^0_{fH_2}$ and $H^0_{fO_2}$ are zero at the reference temperature and pressure.

$$\begin{aligned}&H^0_{f-biomass} + m_w\left(H^0_{fH_2O} + H_{vap}\right) = x_1\left(H^0_{fCO} + \int_{298}^{T_g} C_{PCO}dT\right) + x_2\left(\int_{298}^{T_g} C_{PH_2}dT\right) + \\ &x_3\left(H^0_{fCO_2} + \int_{298}^{T_g} C_{PCO_2}dT\right) + x_4\left(H^0_{fH_2O} + \int_{298}^{T_g} C_{PH_2O}dT\right) + x_5\left(H^0_{fCH_4} + \int_{298}^{T_g} C_{PCH_4}dT\right) + \\ &\left(\frac{z}{2} + x_g 3.76\right)\int_{298}^{T_g} C_{PN_2}dT\end{aligned} \qquad (18)$$

The above equation acts as the constraint for the gasification process and forms the basis for adjusting the amount of air to be supplied. The amount of air is adjusted in such a way that total enthalpy of the reactants is equal to that of the products in gaseous form.

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

$$C_p(T) = C_1 + C_2T + C_3T^2 + C_4T^3(KJ/kg) \qquad (19)$$

The sensible heat of each gas species was found by integrating the above equation from the ambient temperature to gasification temperature. The values from C_1 to C_4 are taken (shown in table 3-1) as reported by et.al. **[18]**.

Table 3-1 : - Coefficients of specific heat capacity for various gases species

Species	C_1	C_2	C_3	C_4
N_2	31.2	-1.36×10^{-2}	2.68×10^{-5}	-1.17×10^{-8}
CO_2	19.8	7.34×10^{-2}	-5.60×10^{-5}	1.72×10^{-8}
H_2	29.1	-1.92×10^{-3}	4.00×10^{-6}	-8.70×10^{-10}
CO	30.9	-1.29×10^{-2}	2.79×10^{-5}	-1.23×10^{-8}
CH_4	19.3	5.21×10^{-2}	1.20×10^{-5}	-1.13×10^{-8}
$H_2O(g)$	32.2	1.92×3	1.06×10^{-5}	-3.60×10^{-9}

It was shown that the change in Gibbs free energy for an individual gas is given by:

$$\Delta\bar{g}^0_{f,T,i} = \Delta\bar{H}^0_{f,i} - aT\ln T - bT^2 - \frac{c}{2}T^3 - \frac{d}{3}T^4 + \frac{e}{2T} + f + gT$$

The values from a to g are taken from Probstein and Hicks **[19]** are shown in the table below, along with enthalpy of formation at standard state of 298 K and 1 atm.

Table 3-2 : - Enthalpy of formation and coefficients for Gibbs free energy

Species	$\bar{H}^0_{f,298}$	a	b	c	d	e	f	g
CH_4	-74.8	-74.8×10^{-2}	1.13×10^{-5}	1.32×10^{-8}	-6.65×10^{-12}	-4.89×10^{2}	14.1	-0.223
CO	-110.5	-74.8×10^{-2}	-1.19×10^{-5}	6.38×10^{-9}	-1.85×10^{-12}	-4.89×10^{2}	0.868	-0.0613
CO_2	-393.5	-74.8×10^{-2}	3.12×10^{-5}	-2.45×10^{-8}	6.95×10^{-12}	-4.89×10^{2}	5.27	-0.121
H_2O	-241.8	-74.8×10^{-2}	-3.67×10^{-5}	5.21×10^{-9}	-1.48×10^{-12}	0	2.87	-0.0172

The input for the program is elemental composition of the feedstock and reaction temperature (usually the temperature of the reduction zone). The Matlab program automatically calculates the molecular formula for the biomass in the form of $CH_xO_yN_z$.

$C^* = C/12, H^* = H/1.008, O^* = O/16, N^* = N/14$

$C_N = C^*/C^* = 1, H_N = H^*/C^*, O_N = O^*/C^*, N_N = N^*/C^*$

The system of equations mentioned in this chapter is solved using Newton's Jacobi method using these stoichiometric numbers and accessing various function files for finding equilibrium constants and other thermodynamic properties of various gases involved in the gasification process. Solving these equations, the number of moles of H_2O, CO, CH_4 and N_2 required for the gasification process is obtained. The fraction of gases can be either expressed as wet syngas composition or dry syngas composition by calculating excluding or including moisture content.

3.2. MATLAB RESULTS AND DISCUSSION

The effects of moisture content on syngas elemental composition and HHV of syngas are executed from the Matlab program written based on the model with many simplifying ideal assumptions. There are results that are in a good agreement with the experimental trends and there are also results away from the expectation out of the reality. Despite the slight difference in the percentage of some constituent gases the variation of syngas composition with moisture content is similar for both coffee husk and saw dust. The differences in fact arise from the phisico-chemical nature each biomass material possesses.

3.2.1. Effect of Moisture Content on Syngas Composition

The results are very close to that of Zainal's **[14]** work discussed in literature review section. Both H_2 and CO_2 increase with moisture content whereas CO decreases. CH_4 has shown no significant change and nitrogen showed a slight increase at the end. In fact, the increase in moisture content adds nothing to the amount of nitrogen but while dealing with percentages, but the equilibrium model for the adiabatic condition automatically adjusts the equivalence ratio to maintain the auto-thermal condition and also the reduction of other constituent gases can make the percentage of nitrogen rise. It gives a strong sense that the reduction of % CO while both H_2 and CO_2 increases is due to the water gas shift reaction in which CO and H_2O combine to yield CO_2 and H_2 as it was discussed before in this chapter.

$CO + H_2O \rightarrow CO_2 + H_2$ (Water gas shift reaction)

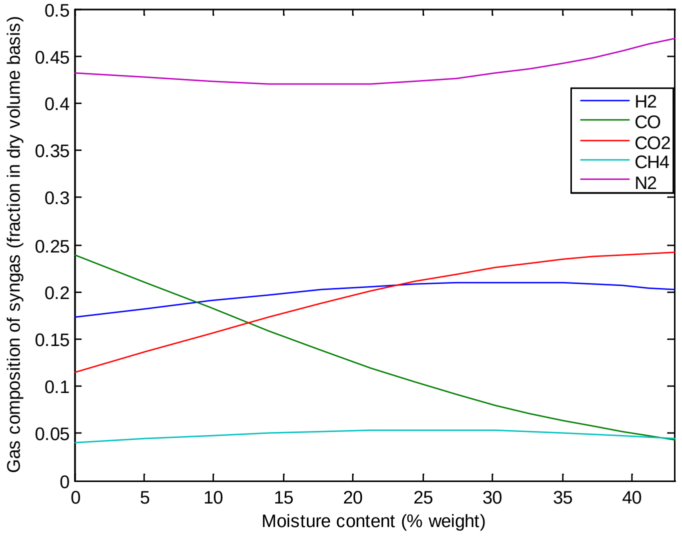


Figure 3-1 : - Effect of moisture content on the gas composition of syngas for adiabatic condition, sawdust as a feedstock

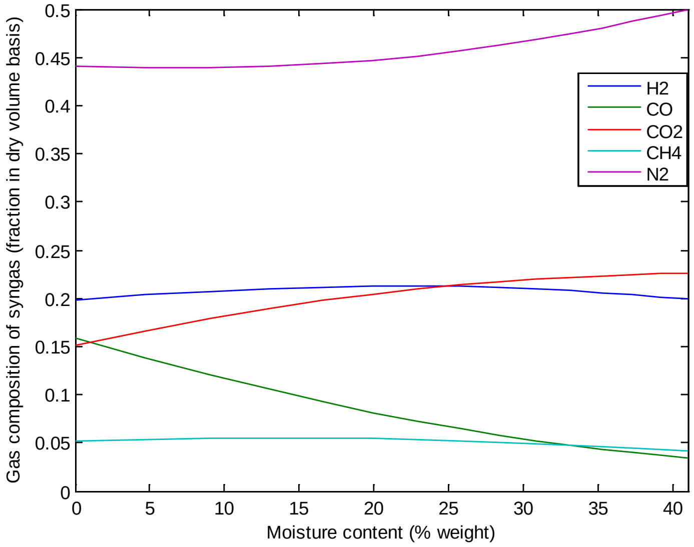


Figure 3-2 : - Effect of moisture content on the gas composition of syngas for adiabatic condition and coffee husk as a feedstock

3.2.2. Effect of moisture content on the HHV of syngas

The heating value of a gaseous fuel is entirely dependent on its gas composition. The constituents that positively contribute to the HHV of syngas are H_2, CO and CH_4 while CO_2 and N_2 are inert. Methane has the highest elemental HHV than H_2 and CO but its concentration in the syngas is very small and so does its impact on the HHV of the syngas. The HHV of the syngas can easily be calculated as:

$$HHV_{syngas} = y_{H2}HHV_{H2}+y_{CO}HHV_{CO}+y_{CH4}HHV_{CH4} \qquad (20)$$

Where, HHV_{H2}= 12.76 MJ/m^3, HHV_{CO}= 12.6 MJ/m^3, and HHV_{CH4}=39.8 MJ/m^3 **[20]**;

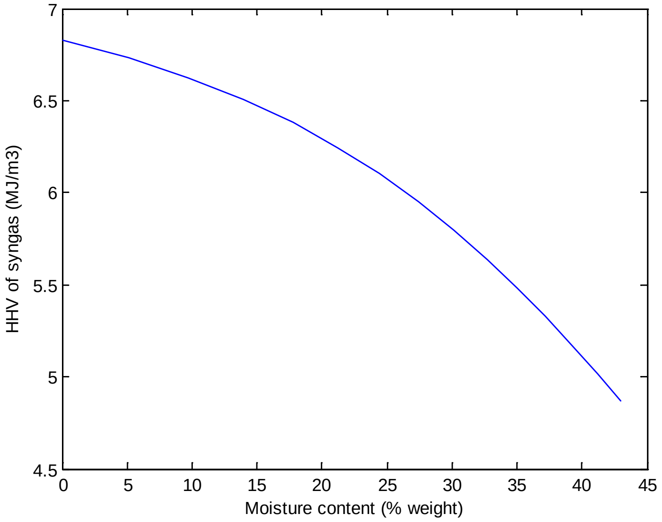


Figure 3-3 : - Effect of moisture content on the HHV of syngas for adiabatic condition, saw dust as a feedstock

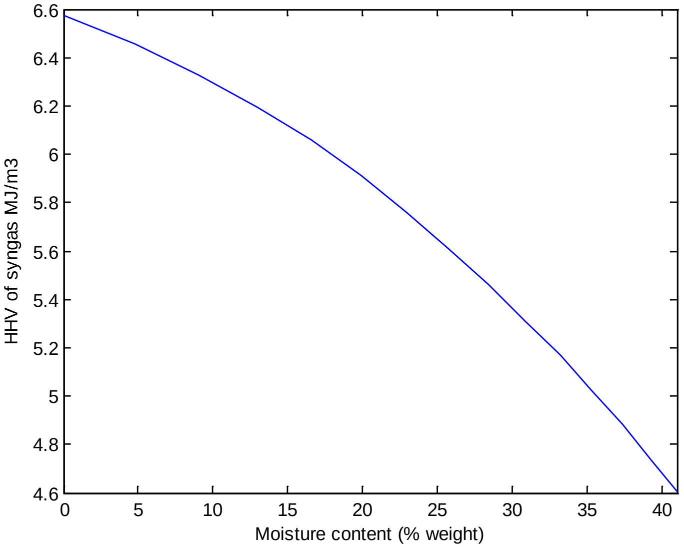


Figure 3-4 : - Effect of moisture content on the HHV of syngas for adiabatic condition, coffee husk as a feedstock

When air is used as a gasifying agent, the enormous amount of nitrogen will dilute the concentration of the important gases which contribute to the HHV of the syngas. This effect is clearly shown in figure 3-3. The heating value of the syngas is much lower than that of the individual constituents which is definitely because nitrogen gas which adds nothing to the calorific value of the gas dominates in concentration. This is an implication of that if pure oxygen was used as a gasifying agent the HHV of the syngas would have been at least doubled in the ideal scenario.

3.2.3. Effect of Equivalence ratio on syngas composition

Equivalence ratio is another decisive parameter in gasification and has a direct effect on the gas composition and calorific value of the syngas. From the figure drawn from the equilibrium model, Both H_2 and CO decreases with increase in equivalence ratio. On the contrary, CO_2 and N_2 increase almost in a linear fashion with equivalence ratio. But this is not always the case when it comes to the real situation.

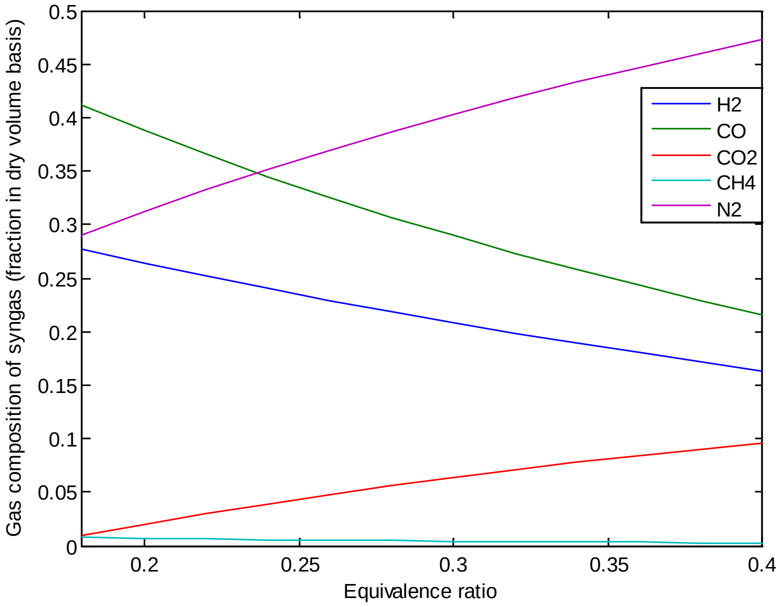


Figure 3-5 : - Variation of syngas composition with equivalence ratio for adiabatic condition, sawdust

On the experimental results of P.M.Lv which was discussed in the literature chapter, both H_2 and CO had shown increasing trend until it reaches to an optimum equivalence ratio, and then decreased in a similar manner to the result in this modeled situation. This mainly is because of the ideal assumption taken in the model formulation. But the oxidation process will get more and more unfavorable as the equivalence ratio decreases, in the real situation. For an equivalence ratio of 0.16 the value for carbon dioxide concentration in the syngas becomes negative which implies an auto-thermal condition is impossible in this equivalence ratio and below.

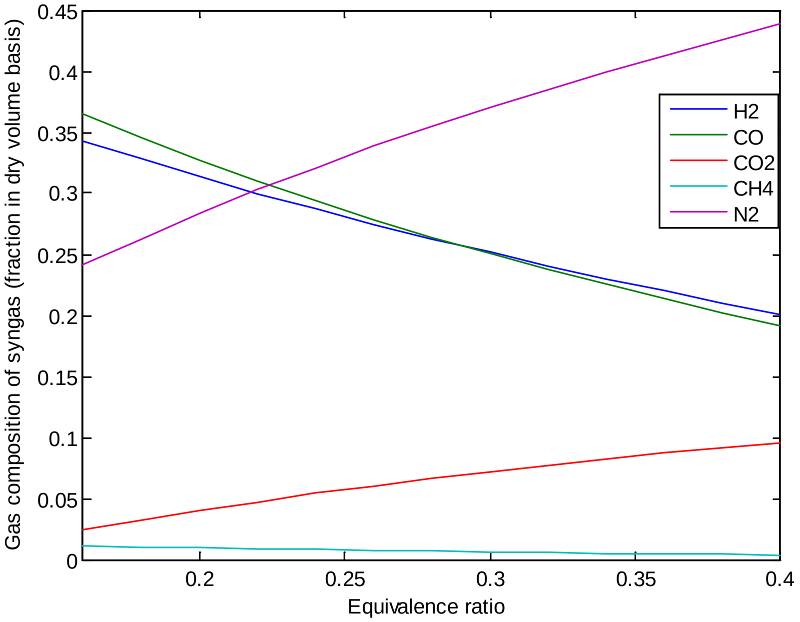


Figure 3-6 : - Variation of syngas composition with equivalence ratio for adiabatic condition, coffee husk

3.2.4. Effect of temperature on Syngas composition and Calorific value

The modeling results of the effect of temperature on syngas composition in both adiabatic and constant ER cases have a very similar nature to the experimental results of Chanchal Loha **[21]**. The increase in temperature favors the production of more CO and H_2 whereas the concentrations of both CO_2 and CH_4 showed reduction with increase in temperature which is in agreement with the experimental results of Chanchal Loha **[21]**. But in the case of the adiabatic condition, the concentration of nitrogen escalated with temperature, which is not convincing since temperature has nothing to do with nitrogen. This is because of that the adiabatic model always adjusts the equivalence ratio to attain the equilibrium auto-thermal condition as there are thermo-chemical changes brought due to change in temperature. A better result is obtained using constant ER model in which nitrogen tends to have a slight decrease with temperature.

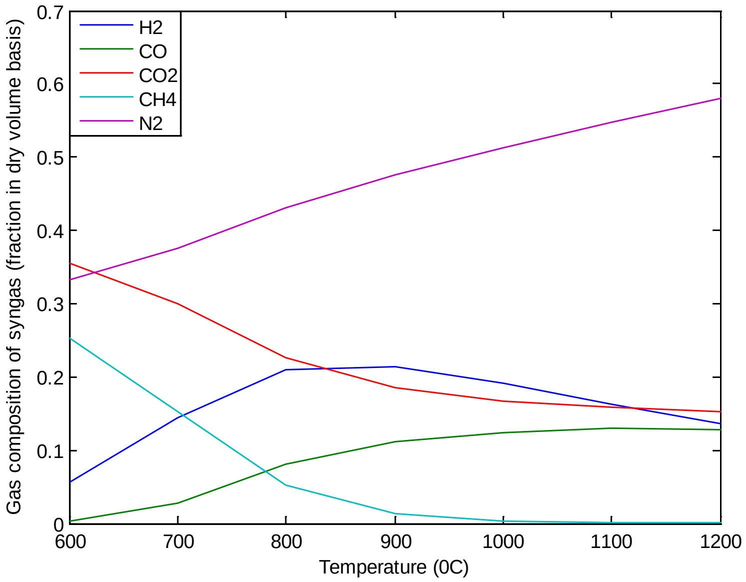


Figure 3-7 : - Effect of temperature on syngas composition for adiabatic condition, sawdust

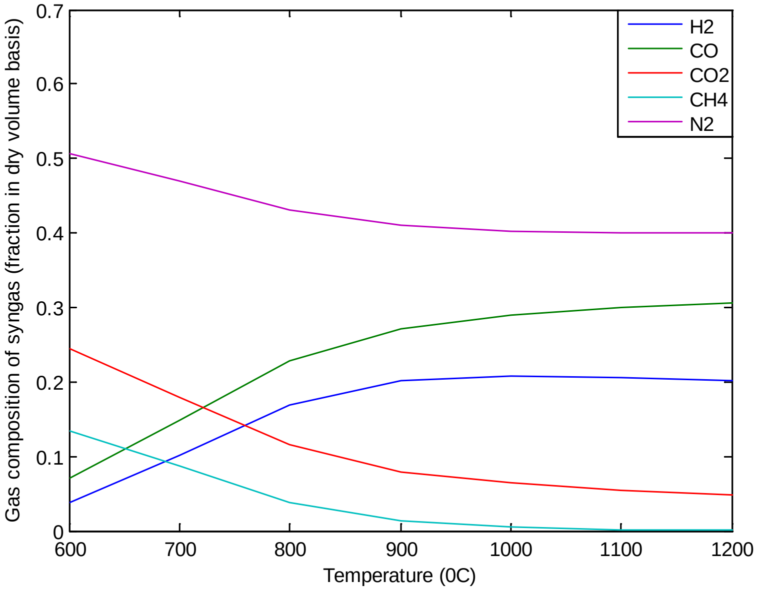


Figure 3-8 : - Effect of temperature on syngas composition for constant equivalence ratio, sawdust

A good comparison of the effect of temperature on the HHV of syngas is presented in the figure below. There is a wide variation between the two models regarding the heating value unlike the syngas composition. The adiabatic model executes that there is a drastic drop in syngas heating value while temperature increases. This is because the effect is dominated by the exaggerated concentration of methane gas together with its incomparably high calorific value among the constituent gases in syngas. Thus, the abrupt decrease in methane concentration means an abrupt decrease in the HHV of syngas. The HHV of syngas for the constant ER model is nearly constant even though the temperature variation is as wide as between 600 and 1200. However, it looks more practical than that of the adiabatic model.

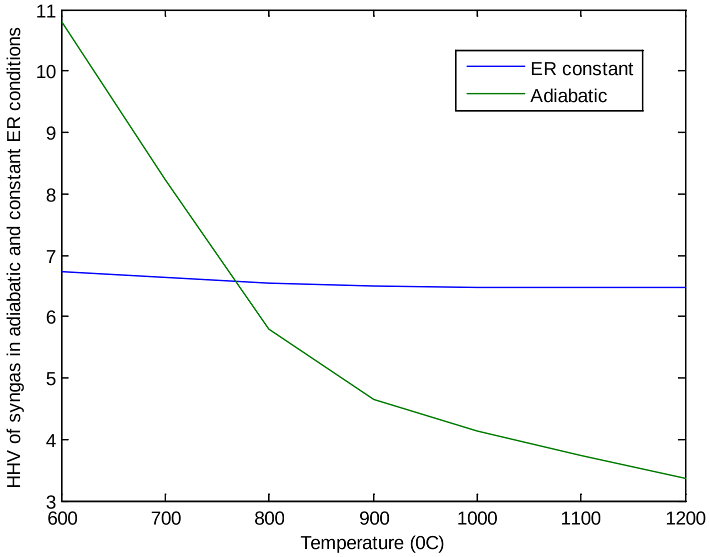


Figure 3-9 : - Comparison of effect of temperature on HHV of syngas in the case of adiabatic and constant ER condition, sawdust

CHAPTER FOUR

EXPERIMENTAL STUDY

4.1. SYSTEM DESCRIPTION

A downdraft BECE gasifier in the workshop of Mechanical Engineering department, Addis Ababa University has been used to undertake the experimental investigation of this thesis work. BECE (Biomass Energy Consultants and Engineers) gasification systems have been manufactured since 1982. It is an integrated system in which the produced gas from the gasifier outlet drives an IC engine after passing through successive gas cleaning units. The engine again drives a water pump for irrigation. Since it is a commercial gasifier it has its company specification to work on with a claim that the gasifier will give its best output.

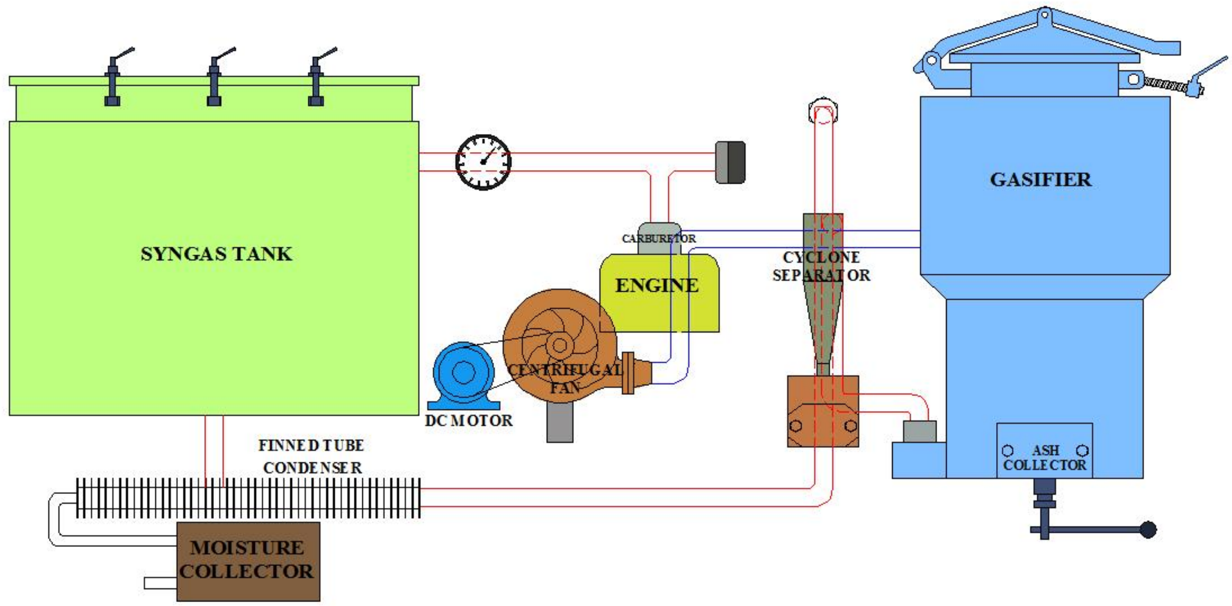


Figure 4-1 : - Schematic diagram of a BECE integrated gasification system for engine application

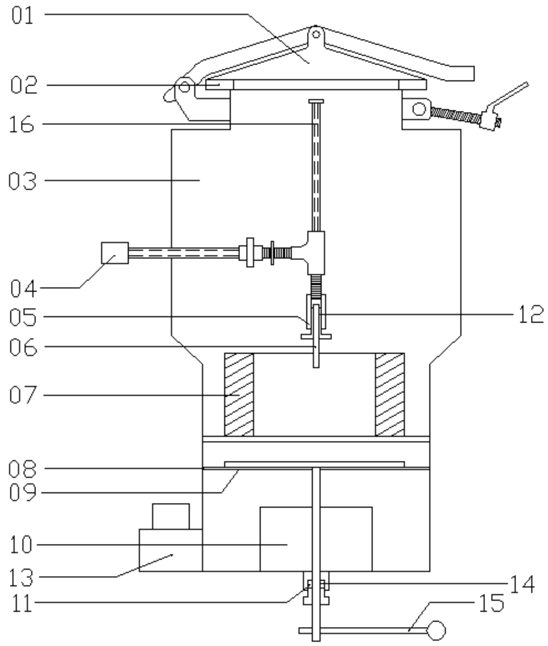
The technical specifications as mentioned on the gasifier manual are as follows:

Technical Specifications

1. Model : BECE – HK 15
2. Type : down – draft gasifier
3. Fuel : charcoal

4. Max. gas production : 75 Nm3/hr
5. Min. gas production : 15 Nm3/hr
6. Gas heating value : approx. 4000 kJ/Nm3
7. Max. fuel moist. Content : 15 % wt
8. Max. fuel ash content : 6 % wt
9. Max. fuel size : 25*25*50 mm
10. Min. fuel size : 10*10*10 mm
11. Fuel size distribution : even distribution
12. Min. fuel bulk density : 100 kg/m3
13. Fuel feeding system : manual
14. Maximum volatile content : 20 % wt
15. Fuel feeding cycle: approx. 3 hrs.
16. Ash removal system : manual

The reactor or the gasifier itself is the primary component of the integrated system in which partial oxidation is undertaken to release gaseous fuel. The principal sketch of the gasifier is shown in Fig 4-2.



P. No	Description
01	Sluice top flap
02	Asbestos cord
03	Bunker
04	Main air inlet
05	Gland
06	Ceramic pipe
07	Refractory hearth ring
08	Stailess steel ring
09	Grid
10	Ash removal hatch
11	Gland
12	Packing
13	Producer gas outlet
14	Packing
15	Grid lever
16	Ignition tube

Figure 4-2 : - Section view and part description of the reactor (gasifier)

Gasification air is supplied through the main air inlet pipe from the air supply fan. An ignition tube is also traversed through the center line of the gasifier to the gland where ignition is started. Once ignition is started the biomass is fed into the gasifier manually and the air supply fan is switched on. The gasifier is covered by a sluice top flap which has an asbestos cord in its periphery to prevent leakage and thermal loss. It can be tightened and loosen by a screw mechanism. There is an ash removal hatch which collects the ash during operation and the ash will be disposed manually after operation. There is a stirrer which is operated by a grid lever beneath the reactor.

The air supply fan is one of the basic components of the integrated system. It is a centrifugal fixed speed fan with the following specifications.

Table 4-1 : - Specifications of the startup centrifugal fan for the BECE gasification system

Flow m^3/min	total pressure differential (Pa)	Voltage V	RPM Min^{-1}	Power kW
1	3500	24	3000	0.37

As the output gas is used to fuel an IC engine it needs a good cleaning system before it enters the engine. The gas cleaning system comprises a cyclone separator, a finned type condenser and cloth filters. There are three thermometers placed at the gasifier gas exit, cloth filter gas inlet and engine gas inlet which measures temperatures below 550 ^{0}C, 250 ^{0}C and 50 ^{0}C, respectively, which serves as control parameters.

4.2. SYSTEM OPERATION

The experiment was conducted using the BECE downdraft gasifier that was described in the above section. Four types of biomass material which are locally available were selected to study the effects of different parameters on gasification of those feedstocks. Coffee husk and wood chips were the major candidates while charcoal was also involved for the sake of comparison. The gasifier was primarily designed to operate with charcoal but it needs a very careful feedstock preparation for it to operate smoothly and give the desired high quality gas to drive the engine (an integral part).

The first step to start the gasification is to put ignition fuel (charcoal in this case) inside the gasifier, in the oxidation zone. Once the charcoal becomes red hot the feedstock is fed from the top of the gasifier manually. A sealed cover is at the top of the gasifier which is closed and tightened using a screw and arm mechanism after once the feedstock is let in, so as to prevent any gas and thermal leakage through the top cover.

Figure 4-3 : - Coffee husk

Figure 4-4 : - Sawdust

On an average, 20 kg of feedstock was fed in to the gasifier for a single run which lasts for about 3 hrs. In fact, the gasifier manual says 45 kg of feedstock per each run but it was found to be impractical. It was necessary to stir the feedstock at least in each 30 min run using a stirrer mechanism beneath the gasifier. It ensures that the consumed biomass that was near the oxidation zone should be substituted and the ash should be disposed down to the ash collector.

It was tried to register the temperatures in the different zones of the gasifier, the syngas out temperature, the flow rate of syngas (indirectly) with in an interval of five minutes. K-type thermocouples with digital data reader were used to measure the temperatures in the pyrolysis, oxidation and reduction zones of the gasifier.

Figure 4-5 : - Fuel feeding mechanism (manual)

The thermocouples were inserted through a tap hole that was primarily made by the manufacturer. It was properly sealed using a fiber glass material to avoid any gas or thermal leakage as well. The temperature of the syngas after it leaves the gasifier is registered by an analog thermometer, in built to the gasifier. A highly sensitive vane type speed meter with a digital register was used to measure the speed of the syngas flow through a hole, which is an indirect measurement of the flow rate of the syngas.

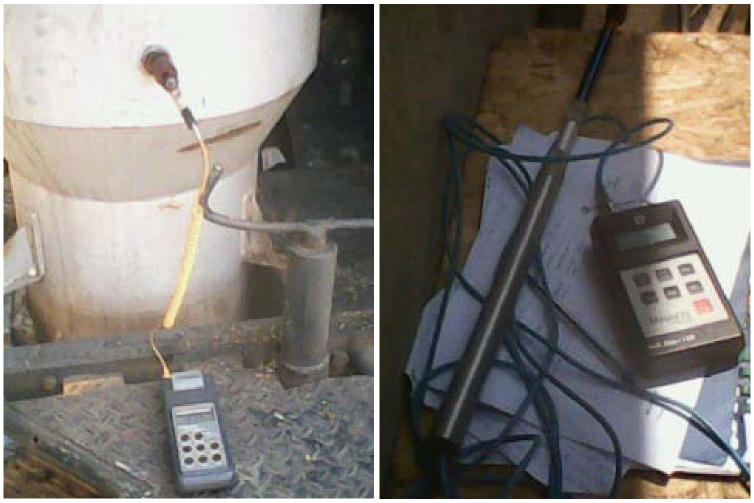


Figure 4-6 : - A K-type thermocouple (left) and vane type speed meter (right)

As far as output is concerned, the interest is on the elemental composition and calorific value of the producer gas, so that it is of primary interest to know the syngas composition and its calorific value. A gas chromatograph is an ideal equipment to know the elemental composition of the syngas to a sufficient accuracy. Due to the unavailability of Helium gas inland, an Orsat analyzer was used instead, which is of less reliability and a bit difficult to operate. The Orsat analyzer only measures the amount of Carbon Monoxide, Carbon Monoxide and Oxygen only. The Nitrogen gas can be estimated from the amount of air that was fed through the air inlet nozzle for oxidation during the gasification process, assuming that the inherent nitrogen inside the biomass is negligible. Therefore, the composition of the hydrogen gas can be estimated by calculating the difference. The flame property has served as a good parameter in order to make an educated guess on the calorific value of the produced gas. The liquid and particulate collector beneath the cyclone separator collects both vapor and tar together with other particulates. The water and tar mixture liquid were collected after each run of the gasification so as to compare the amount of tar produced for different feedstocks and various operating conditions.

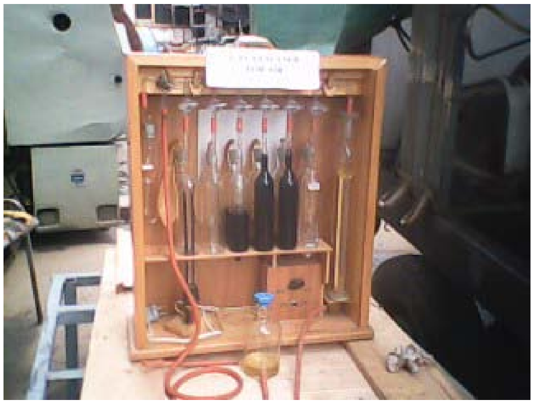


Figure 4-7 : - An Orsat gas analyzer

4.3. DATA COLLECTION AND ANALYSIS

As it was mentioned earlier four types of feedstock were chosen to undertake the experimental investigation. The study is intended to see the nature of the produced gas using different biomass materials that are locally and easily available and to see the effects of different parameters on the syngas characteristics. Coffee husk, saw dust, and a hybrid of coffee husk and saw dust were the major candidate for the experiment while charcoal was tested just for comparison. Syngas was directed to the orsat analyzer through a tube and the individual gas composition was measured in a volume basis. Only CO, CO_2 and O_2 can be measured using the Orsat analyzer so that H_2 is found by calculating the difference while N_2 was estimated from that of the amount of nitrogen inside the gasification air. The Orsat analyzer was calibrated with air for oxygen. The higher heating value of the syngas was calculated by multiplying the volumetric composition of the individual constituents by their respective higher heating values.

$$HHV_{syngas} = y_{H2}HHV_{H2}+y_{CO}HHV_{CO}+y_{CH4}HHV_{CH4}$$

The HHV of H_2, CO and CH_4 are 12.76 MJ/m^3, 12.6 MJ/m^3 and 39.8 MJ/m^3, respectively **[20]**.

A sample of the biomass material before each run have been taken and heated inside a micro wave oven for about 3 hrs at a constant temperature of 112 ^{0}C. The sample after drying is carefully weighted using a digital weight meter. The percent of moisture content by weight was easily calculated in a wet basis. Since there is no laboratory set up to do ultimate and proximate analysis, it was only taken from literatures for further analysis of the experimental work.

4.4. RESULTS AND DISCUSSION

4.4.1. Effect of moisture content

The effect of moisture content was studied and fairly effective figures of it are derived so as to make validation. The results are in a good agreement with the modeling results and also some experimental results in literatures, despite the absence of methane concentration which was impossible to find out with an Orsat gas analyzer.

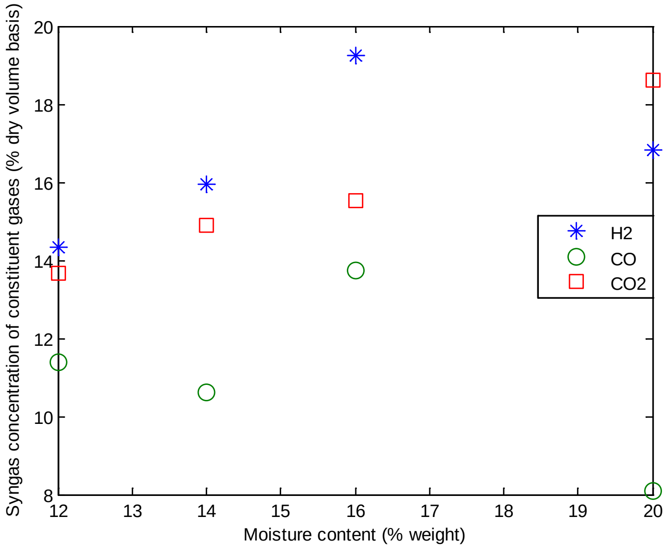


Figure 4-8 : - Effect of moisture content on syngas composition, coffee husk

Hydrogen production usually escalates with increase in moisture content as it was also observed in the equilibrium model result. But it tends to lower after some point, which as it was described in the literature review part, is because much moisture content more than that of the optimum will retard the pyrolysis reaction, which results in reduction of hydrogen production. The trend shown by CO_2 and CO is much similar to the model result and the one reported by Zainal **[14]**, except that CO has experienced an unexpected value at 16 % moisture content. The exceptionally favorable condition created in this moisture content might have brought the concentration of both H_2 and CO to attain their pick values at this point. As coffee husk has low fixed carbon content and high volatile matter, it looks convincing that CO concentration stayed at the bottom of the graph, while hydrogen at the top.

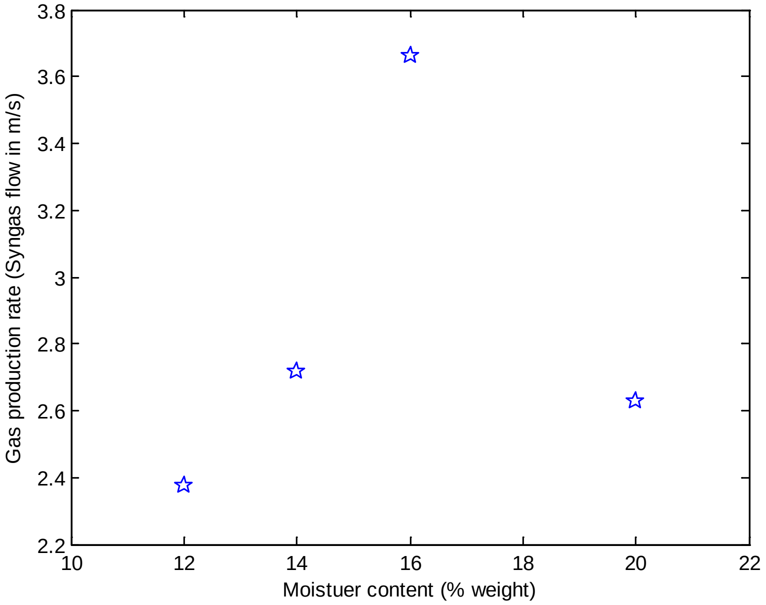


Figure 4-9 : - Effect of moisture content on syngas production rate, coffee husk

4.4.2. Timely fluctuation of syngas flow and temperature

The gas production rate as it is shown from the figure, generally shows increasing trend with time. This is the outcome of the increase in temperature of the different zones of the gasifeir as time goes on, and it creates a more favorable condition for the partial oxidation which in turn gives rise to the increase in gas production rate. There are points in which the syngas flow drops and shoots up abruptly. Since the feedstock is fed manually once as a whole, biomass consumption rate will not be constant throughout the running duration. As the biomass around the oxidation zone gets consumed the syngas production starts to decline until the feedstock is redistributed manually. This again brings the similar effect on the temperature of the pyrolysis zone as it is shown in figure.

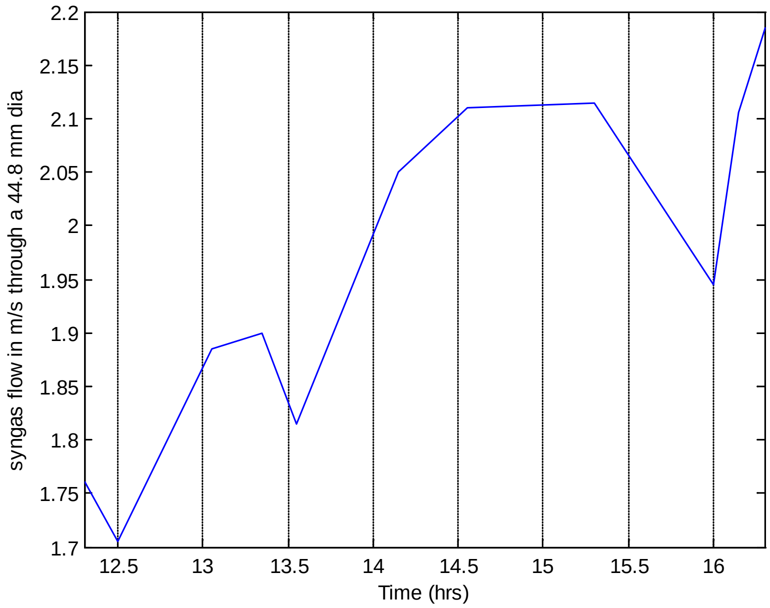


Figure 4-10 : - Syngas flow variation with time, Charcoal

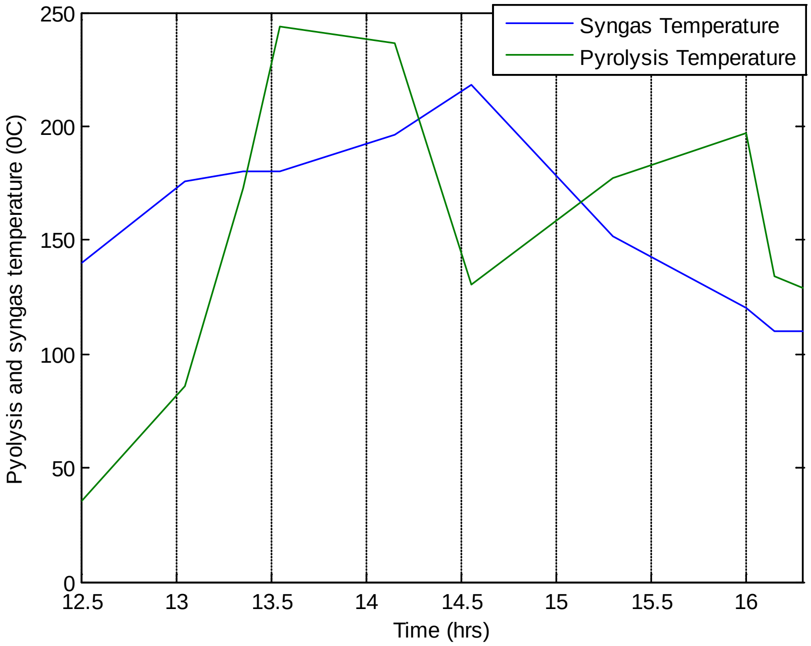


Figure 4-11 : - Temperature fluctuation of syngas and pyrolysis zone with time, Charcoal

The three turning points which are near 13:50, 14:50 and 16:00 are the consequences of the opening and manual distribution of the gasifier and feedstock, respectively. Some air will get in while attempting to redistribute the feedstock which also aids the syngas production rate as more air accelerates the rate of combustion. Feedstock particle size and geometry is critically decisive for the stable operation and good thermo chemical behavior of the gasification process. Had feedstock pretreatment been undertaken prior to gasification, problems related to distribution and fluctuation would have been minimized.

The table below presents the average syngas flow speed in m/s through a 44.8 mm dia opening. It is another manifestation of the syngas production rate. Syngas production rate is maximum for coffee husk and minimum for charcoal.

Table 4-2 : - Average syngas rate for different feedstocks

Feedstock	Charcoal	Coffee Husk	Sawdust	Mix. of Sawdust and coffee husk
Syngas flow (Avg.) (m/s)	1.961	2.716	2.609	2.502

4.4.3. Flame Characteristics

Visual inspection can help to comparatively judge the calorific value and gas composition of syngas from different feedstock and the common one is flame characteristics. An excellent (high intensity) and consistent flame was observed for the hybrid feedstock from coffee husk and sawdust. Based on this judgment sawdust charcoal and coffee husk are very good, good and fair, respectively.

Figure 4-12 : - Flame characteristics for visual inspection

4.4.4. Amount of tar for different feedstock

Samples of tar content for the various feedstock studied were taken in order to have a comparative figure of tar content of the respective feedstocks. Even though tar is not a serious concern for a downdraft gasifier as many literatures claimed, in this experiment considerable challenge have been experienced due to tar formation and its effect when coffee husk and sawdust were used. The problem was much pronounced for the case of sawdust, and a mixture of sawdust and coffee husk. On the other side, no significant observation of tar formation while the gasifier operates with charcoal has been experienced.

Figure 4-13 : - A highly viscous tar leaving through a tap hole near the pyrolysis zone

4.5. CHALLENGES AND MEASURES

At the beginning of the experimental work a great deal of problem related to supplying power to the blower has been faced. The blower is driven by a DC motor with a rating of 12 V and 26 amps, and requires above 40 amps starting current. A motor with this specification is not available in the local market. Various options were tried to overcome this problem until when a potential solution was brought with the cooperation of the Electrical Engineering department, with both laboratory equipments and human skill. Eight DC power suppliers were made to be connected in parallel fashion, which adds the current drawn from each supplier, while the voltage is adjusted to 12 V, similar for each DC supplier. Each supplier can draw 6 amps, so that a total of 48 amps can be obtained, which is more than enough to run the motor.

To prepare the gasifier for testing, cleaning is compulsory. The gasifier sections, the ash bunker and the cyclone separator were cleaned manually and using a compressor. Due to lack of experience, it was a bit difficult to have an easy starting of the combustion.

The system is an integrated system having the gasifier unit, piping system, gas cleaning units, a tank to store syngas and an engine working with syngas and gasoline. The gasoline is used as a fuel for the engine before the gasifier begins producing syngas. The engine, in turn, drives a fan to supply air to the oxidation zone of the gasifier just enough to maintain the desired partial oxidation.

The system has not been working for many years because no attention has been paid to it. As a result, some of its parts and components were subjected to temporary and permanent failure. The first action taken was to start the engine alone without any integration with the gasifier unit. Before any attempt to troubleshoot the system, it was tried to start the engine with the key, which was properly kept in Mechanical Engineering workshop. The battery was dead due to prolonged life being kept idle. Two other batteries from Mechanical Engineering were tried and being unsuccessful a good working battery was unloaded from a car that belongs to Mr. May, which had helped a lot for the first engine test. Well, the new battery has worked and removed the first obstacle, but still the engine failed to have its shaft rotated.

Through patient investigation it was found that the starter motor was not operational because it was rusted and got stuck. It was taken out from its place, get cleaned and lubricated well; as a result it started working properly after it was tested separately. This still didn’t make the engine to start and run properly. There was still another problem to be discovered and resolved so as to make the engine operational. It was found out that the pump that was coupled to the engine shaft was seized, rusted and the impeller got stuck with the casing which inhibits the engine shaft to rotate. Dismantling the pump and removing its coupling from the engine shaft, the engine could start but still failed to run self actuated. That was an indication of another potential problem still existed that made the engine operation unsuccessful.

To avoid any circumstance that subjected the malfunctioning of the engine, the spark plugs were disassembled and got cleaned with a wire brush and benzene. It was considered that the improper functioning of the Carburetor was responsible for the remaining problem left with the engine. In the next day, the Carburetor was thoroughly cleaned with a wire brush and benzene, its worn out gasket was changed with a replica cut from a water proof hard paper, and finally fixed to its place. This in fact, has brought a better status of the failed engine.

During engine testing after the carburetor was troubleshot, a back fire was noticed which is probably resulted from a timing problem in the exhaust valves. With further inspection, it was also found that the water outlet from the engine to the radiator was got crude and cooling water could not reach the engine. Even though the engine started running successfully, it failed to maintain it and switched off due to over speed. The carburetor had also needed adjustment to give a steady running.

In the next few days, works that have made the engine to have much better operational status and smoother start-up had done. It was found that the thermostat inside the cooling water line from the engine to the carburetor had prevented the proper flow of the cooling water. The thermostat was simply made to get rid of the system and the cooling water tube connecting the engine and the carburetor was properly fixed and tightened to avoid any leakage. It was then after that a proper operation of the cooling system observed.

The possible firing order for the V-6 engine type was referred from the internet. The cables from the distributor to the spark plugs of the respective engine cylinders are arranged according to the correct firing order. Till the timing was brought to the correct one the engine had experienced a difficulty of smooth start-up. It was finally adjusted using a spark light and revolution alignment sensors.

CHAPTER FIVE

LIMITATION, RECOMMENDATION AND FUTURE WORKS

5.1. LIMITATIONS

There have been strong limitations which affect the thesis work both in scope and quality. The air supply fan is driven by a DC powered motor which was the first and most challenging problem faced during the experimental task. It was tried to use DC power suppliers instead of AC directly from the line, and in fact so tedious. Moving eight DC suppliers together with a long power cable, connecting them in each and every day of operation was tiresome and time consuming.

Equivalence ratio was supposed to be one of the very important parameters to be studied in this research but was skipped because the motor that drives the air supply fan was fixed speed. It had to vary the air supply in order to study the effect of equivalence ratio, which needs a variable speed motor.

The elemental composition of the producer gas is the foremost entity needs to be known to an acceptable accuracy. But, the absence of Helium gas which acts as a career gas while a gas chromatograph is in the chemical laboratory makes the work very complicated. Though, an Orsat analyzer was used instead, but it lacks reliability and accuracy, as it does not measure hydrogen and also due to other technical problems.

Another major limitation that was faced in this thesis work was labor based task that was involved in the experiment. It was a bit uncomfortable to carry both labor and technical responsibilities at a time. Tar sticking inside the pipes and through gas cleaning lines was troublesome. For example, the thermometer that measures the temperature of the syngas as it leaves the gasifier was not measuring properly due to tar sticking on the inside surface of the pipes.

5.2. RECOMMENDATIONS

Attention should be given to thesis works that involve manufacturing and experimental tasks. There are very precise laboratory equipments but some are not operational due to minor problems, particularly the gas Chromatograph due to absence of Helium gas and the Bomb calorimeter due to shortage of Oxygen. Problems that can be solved by the department should be addressed earlier before students start working their thesis in this area.

5.3. FUTURE WORKS

A lot of works can be done as an extension of this thesis work since its scope is so wide and its practicality is so promising. Feed stock preparation is one area to be investigated that is not addressed in this paper, starting from the design of the mechanism for feedstock preparation, studying of its economic feasibility from local and national perspectives and preparing a manual for best combination of different operating conditions with different feedstock physical nature.

It seems that a lot has to be done on extensive study of the potential of biomass based energy to guarantee the future energy demand of Ethiopia. As a first work, this paper is concentrated on a few biomass feedstock that are very common (like coffee husk and saw dust) and as simple as to be recommended by any lay person, to be used as energy sources.

Advancing and refining the works done in this research work are also other ways to look for in the future. It can be an innovative design of a gasifier that can give a better result in one of the studied parameters. For example, a hybrid solar thermal gasification would give better gasification efficiency, or some other innovative design can give a solution for the inherent tar formation and its nasty effect on the operation of the gasifier and the applicability of the producer gas.

Most importantly it is very impressive to think of the applicability of the produced gas. The gas, despite its low energy density compared to petroleum products, can be used for widespread applications ranging from direct thermal application (for example, drying) to high level applications like engines and gas turbines. So, it needs both design and experimental works to insure the practicality of the producer gas for various applications. Design and test of gas cleaning mechanisms, thorough experimental investigation of the quality and reliability of the processed gas to decide whether it fits or not to the intended application and making a practical work to present it to the market are the major tasks foreseen by the author.

APPENDIX A

MATLAB CODE FOR SYNGAS EQUILIBRIUM MODELING FOR ADIABATIC CONDITIONS

A.1 MAIN FUNCTION FILE

```
%THIS PROGRAM IS SET TO GIVE SYNGAS COMPOSITION IN DRY SYNGAS BASIS. IF FOR
%SOME REASON YOU WANT TO CHANGE, PLEASE MODIFY IN LINE 113 AND 114.
function[final_frac_comp]=eq_comp_model_gen(g_temp,ele_comp)
format short
tol=0.0001;
maxit=100;
%disp('elemental composition should be of the form [C, H, O, N, Ash]');
%ele_comp=input('Enter elemental composition of biomass: ');
%disp('Initial guess is of the form [H2 CO CO2 H2O CH4 3.76N2] ')
xx0=[0.1,0.1,0.1,0.1,0.1,0.1]';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Heat of formation of different compounds at 25 C, kJ/kmol
H_f_H2O_g=-241818;H_f_H2O_l=-285830;H_f_CO2=-393509;H_f_CO=-110525;
H_f_CH4=-74520;H_f_H2=0;H_f_O2=0;H_f_N2=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Function for finding sensible heat for various gases
%constants
C_p_H2O=[32.24 0.1923e-2 1.055e-5 -3.595e-9];
C_p_H2=[29.11 -0.1916e-2 0.4003e-5 -0.8704e-9];
C_p_CO=[28.16 0.1675e-2 0.5372e-5 -2.222e-9];
C_p_CO2=[22.26 5.981e-2 -3.501e-5 -7.469e-9];
C_p_CH4=[19.89 5.204e-2 1.269e-5 -11.01e-9];
C_p_N2=[28.90 -0.1571e-2 0.8081e-5 -2.873e-9];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding general equations for calculating k1 and k2
G_CO=[3.376 0.557e-3 0 -0.031e5 -110525 -137169];
G_CO2=[5.457 1.045e-3 0 -1.157e5 -393509 -394359];
G_H2O=[3.470 1.450e-3 0 0.121e5 -241818 -228572];
G_H2=[3.249 0.422e-3 0 0.083e5 0 0];
G_C=[1.771 0.771e-3 0 -0.867e5 0 0];
G_CH4=[1.702 9.081e-3 -2.164e-6 0 -74520 -50460];
delta_ws_final=[];
delta_meth_final=[];
for iii=1:6
delta_ws=G_H2(iii)+G_CO2(iii)-G_CO(iii)-G_H2O(iii);
delta_meth=G_CH4(iii)-G_C(iii)-2*G_H2(iii);
delta_ws_final=[delta_ws_final delta_ws];
delta_meth_final=[delta_meth_final delta_meth];
end
T_0=298;
k1=exp(-((delta_meth_final(6)-
delta_meth_final(5))/(8.314*298.15)+(delta_meth_final(5)/(8.314*g_temp))...
```

```
+(int_eq_sp2(delta_meth_final,g_temp)/g_temp)-
int_eq_sp1(delta_meth_final,g_temp)));
k2=exp(-((delta_ws_final(6)-
delta_ws_final(5))/(8.314*298.15)+(delta_ws_final(5)/(8.314*g_temp))...
+(int_eq_sp2(delta_ws_final,g_temp)/g_temp)-
int_eq_sp1(delta_ws_final,g_temp)));
%%%%%%%%%%%%%%%%%%%%%%%%%%
%function for calculating int_eq_sp
function int_for_gibbs_difff1= int_eq_sp1(difff,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff1=difff(1).*log(tau)+((difff(2).*T_0+...
((difff(3)*T_0^2+(difff(4)/(tau^2.*T_0^2)))*((tau+1)/2)))*(tau-1));
end
function int_for_gibbs_difff2= int_eq_sp2(var_sp,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff2=var_sp(1).*T_0*(tau-1)+...
var_sp(2)*0.5*T_0^2*(tau^2-1)+var_sp(3)*T_0^3*(tau^3-1)/3+...
var_sp(4)*(tau-1)/(tau*T_0);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%finding lambda and gamma for below calculation%%%%%%%%%%%%%%%%%%%%%%%%
norm_1_C=ele_comp(1)/(12);
norm_1_H=ele_comp(2)/(1.008);
norm_1_O=ele_comp(3)/(16);
norm_1_N=ele_comp(4)/(14.007);
lambda=norm_1_H/norm_1_C;
gamma=norm_1_O/norm_1_C;
beta=norm_1_N/norm_1_C;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x0=xx0;
iter=1;
iter_m=1;
sol_final=[];
%w=M_fs*Moisture_Content/(18*(1-Moisture_Content));
w=linspace(0,1,15);
%w=0;
Moisture_Content=[];
M_fs=12+lambda*1.008+gamma*16;
for N=1:length(w)
Moisture_Content=[Moisture_Content 18*100*w(N)/(M_fs+18*w(N))];
end
Moisture_Content
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Main Loop for solving the equations of interests
for iter_m=1:length(w)
while(iter<=maxit)
y=-df1(x0)\f1(x0);
xn=x0+y;
err=max(abs(xn-x0));
```

```
if(err<=tol)
x=xn;
else
x0=xn;
end
iter=iter+1;
end
iter=1;
sol_temp=x;
%%%%%%%%%%%%%%%%%%Continued
below%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sol_final=[sol_final sol_temp];
iter_m=iter_m+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%Multiplying m with 3.76 to get correct N2 mols
p=length(w);
frac_N2=[];
for l=1:p
frac_N2=[frac_N2 sol_final(6,l)*3.76];
end
final_comp=[sol_final(1:5,1:p);frac_N2]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%fin_rep=input('Do you want to find syngas composition in dry syngas
basis(y/n): ','s');
fin_rep='y';
if fin_rep=='n';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas for each moisture content
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(final_comp(1:6,n))];
end
total_frac_m; %sum of all product gases
else
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas on dry basis for each moisture
%content
dry_final_comp=final_comp;
dry_final_comp(4,:)=[];
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(dry_final_comp(1:5,n))];
end
total_frac_m;
final_comp=dry_final_comp;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%expressing all the components in molar fraction or volumetric fraction
```

```
final_frac_comp=[];
for MM=1:length(total_frac_m)
final_frac_m=[];
if fin_rep=='y'
l_in=length(xx0)-1;
else
l_in=length(xx0);
end
for NN=1:l_in
final_frac_m=[final_frac_m;final_comp(NN,MM)/total_frac_m(MM)];
end
final_frac_comp=[final_frac_comp final_frac_m];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function f=f1(X)
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);m=X(6);
val_1=x_2+x_3+x_5-1;
val_2=x_1+x_4+2*x_5-w(iter_m)-(lambda/2);
val_3=x_2+2*x_3+x_4-2*m-gamma-w(iter_m);
val_4=-k1*x_1^2+(x_5*(x_1+x_2+x_3+x_4+x_5+3.76*m));
val_5=x_2*x_4*k2-x_1*x_3;
val_6=x_1*t_en_gas(H_f_H2, C_p_H2, g_temp)+...
x_2*t_en_gas(H_f_CO, C_p_CO, g_temp)+...
x_3*t_en_gas(H_f_CO2, C_p_CO2,g_temp)+...
x_4*t_en_gas(H_f_H2O_g, C_p_H2O, g_temp)+...
x_5*t_en_gas(H_f_CH4, C_p_CH4, g_temp)+...
3.76*m*t_en_gas(H_f_N2, C_p_N2, g_temp)-...
heat_bio(ele_comp)-w(iter_m)*(H_f_H2O_l+1000);
f=[val_1; val_2;val_3;val_4;val_5;val_6];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function df=df1(X);
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);m=X(6);
df=[0,1,1,0,1,0;1 0 0 1 2 0; 0 1 2 1 0 -2;-
2*x_1*k1+x_5,x_5,x_5,x_5,2*x_5+(x_1+x_2+x_3+x_4+3.76*m),3.76*x_5; -x_3
k2*x_4...
-x_1 k2*x_2 0 0; t_en_gas(H_f_H2, C_p_H2, g_temp)...
t_en_gas(H_f_CO, C_p_CO, g_temp) t_en_gas(H_f_CO2, C_p_CO2, g_temp)...
t_en_gas(H_f_H2O_g, C_p_H2O, g_temp) t_en_gas(H_f_CH4, C_p_CH4,
g_temp)...
3.76*t_en_gas(H_f_N2, C_p_N2, g_temp)];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function dh_comp=t_en_gas(H_for, sp_heat, temp)
heat_coeff=sp_heat;
dh_comp=H_for+quad(@sensible,298,temp);
function sens_heat=sensible(t)
sens_heat=heat_coeff(1)+heat_coeff(2).*t+heat_coeff(3).*t.^2+heat_coeff(4).*t.^3;
end
```

```
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Standard heat of formation of various biomass
%H_f_XX is the heat of formation of XX compound, units in kJ/kmol
%LHV is lower heating value of biomass, kJ/kg
%LHV_mol is the lower heating value of biomass, kJ/kmol
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function H_f_bio= heat_bio(comp)
LHV=4.187*(81*comp(1)+300*comp(2)-26*comp(3)-54*comp(2));
LHV_mol=LHV*(12+lambda*1.008+gamma*16);
H_f_bio=(lambda/2)*H_f_H2O_l+H_f_CO2+LHV_mol;
end
end
```

A.2 FUNCTION FILE FOR FINDING EQUILIBRIUM CONSTANTS

```
%Program for finding equilibrium constant for various reaction
%Rxn-1: CO+H_2O=CO_2+H_2
%Rxn-2: C+2H_2=CH4
function[k]=Delta_G(T)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding general equations for calculating k1 and k2
G_CO=[3.376 0.557e-3 0 -0.031e5 -110525 -137169];
G_CO2=[5.457 1.045e-3 0 -1.157e5 -393509 -394359];
G_H2O=[3.470 1.450e-3 0 0.121e5 -241818 -228572];
G_H2=[3.249 0.422e-3 0 0.083e5 0 0];
G_C=[1.771 0.771e-3 0 -0.867e5 0 0];
G_CH4=[1.702 9.081e-3 -2.164e-6 0 -74520 -50460];
delta_ws_final=[];
delta_meth_final=[];
for iii=1:6
delta_ws=G_H2(iii)+G_CO2(iii)-G_CO(iii)-G_H2O(iii);
delta_meth=G_CH4(iii)-G_C(iii)-2*G_H2(iii);
delta_ws_final=[delta_ws_final delta_ws];
delta_meth_final=[delta_meth_final delta_meth];
end
T_0=298;
k1=exp(-((delta_meth_final(6)-
delta_meth_final(5))/(8.314*298.15)+(delta_meth_final(5)/(8.314*T))...
+(int_eq_sp2(delta_meth_final,T)/T)-int_eq_sp1(delta_meth_final,T)))
k2=exp(-((delta_ws_final(6)-
delta_ws_final(5))/(8.314*298.15)+(delta_ws_final(5)/(8.314*T))...
+(int_eq_sp2(delta_ws_final,T)/T)-int_eq_sp1(delta_ws_final,T)))
k=[k1,k2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%function for calculating int_eq_sp
function int_for_gibbs_difff1= int_eq_sp1(difff,T)
tau=T/298.15;
int_for_gibbs_difff1=difff(1).*log(tau)+((difff(2).*T_0+...
((difff(3)*T_0^2+(difff(4)/(tau^2.*T_0^2)))*((tau+1)/2)))*(tau-1));
```

```
end
function int_for_gibbs_difff2= int_eq_sp2(var_sp,T)
tau=T/298.15;
int_for_gibbs_difff2=var_sp(1).*T_0*(tau-1)+...
var_sp(2)*0.5*T_0^2*(tau^2-1)+var_sp(3)*T_0^3*(tau^3-1)/3+...
var_sp(4)*(tau-1)/(tau*T_0);
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

A.3 FUNCTION FILE FOR FINDING THE ENTHALPY CHANGE IN GASES

```
%calculates the total enthalpy change with reference to 298 K of different
%chemical elements in kJ/kg
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function H_Tot=En_Ch(T,S)
switch (S)
case('CO2')
M_Wt=44.0095;HoF=-393.51;
C_p=[22.26 5.981e-2 -3.501e-5 -7.469e-9];
case ('CO')
M_Wt=28.0101; HoF=-110.53;
C_p=[28.16 0.1675e-2 0.5372e-5 -2.222e-9];
case ('CH4')
M_Wt=16.0425; HoF=-74.87;
C_p=[19.89 5.204e-2 1.269e-5 -11.01e-9];
case ('H2O')
M_Wt=18.0153; HoF=-241.83;
C_p=[32.24 0.1923e-2 1.055e-5 -3.595e-9];
case ('N2')
M_Wt=28.01348;
C_p=[28.90 -0.1571e-2 0.8081e-5 -2.873e-9];
case ('O2')
M_Wt=31.9988;
end
H_Tot=(1000/M_Wt)*HoF+quad(@sensible,298,T);
function sens_heat=sensible(T)
sens_heat=C_p(1)+C_p(2).*T+C_p(3).*T.^2+C_p(4).*T.^3;
end
end
%EOF, En_Ch.m
```

APPENDIX B

FUNCTION FILE FOR FINDING SYNGAS COMPOSITION AT CONSTANT EQUIVALENCE RATIO

The functions used for calculating the enthalpy change and equilibrium constants are same as that for adiabatic condition which is already mentioned in appendix A. However, the main function file is different which is as follows.

```
%THIS PROGRAM IS SET TO GIVE SYNGAS COMPOSITION IN DRY SYNGAS BASIS. IF FOR
%SOME REASON YOU WANT TO CHANGE, PLEASE MODIFY IN LINE 113 AND 114.
function[final_comp]=eq_model_const(g_temp,ele_comp,m)
format short
tol=0.00001;
maxit=100;
%disp('elemental composition should be of the form [C, H, O, N, Ash]');
%ele_comp=input('Enter elemental composition of biomass: ');
%disp('Initial guess is of the form [H2 CO CO2 H2O CH4] ')
xx0=[0.1,0.1,0.1,0.1,0.1]';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Heat of formation of different compounds at 25 C, kJ/kmol
H_f_H2O_g=-241818;H_f_H2O_l=-285830;H_f_CO2=-393509;H_f_CO=-110525;
H_f_CH4=-74520;H_f_H2=0;H_f_O2=0;H_f_N2=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Function for finding sensible heat for various gases
%constants
C_p_H2O=[32.24 0.1923e-2 1.055e-5 -3.595e-9];
C_p_H2=[29.11 -0.1916e-2 0.4003e-5 -0.8704e-9];
C_p_CO=[28.16 0.1675e-2 0.5372e-5 -2.222e-9];
C_p_CO2=[22.26 5.981e-2 -3.501e-5 -7.469e-9];
C_p_CH4=[19.89 5.204e-2 1.269e-5 -11.01e-9];
C_p_N2=[28.90 -0.1571e-2 0.8081e-5 -2.873e-9];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding general equations for calculating k1 and k2
G_CO=[3.376 0.557e-3 0 -0.031e5 -110525 -137169];
G_CO2=[5.457 1.045e-3 0 -1.157e5 -393509 -394359];
G_H2O=[3.470 1.450e-3 0 0.121e5 -241818 -228572];
G_H2=[3.249 0.422e-3 0 0.083e5 0 0];
G_C=[1.771 0.771e-3 0 -0.867e5 0 0];
G_CH4=[1.702 9.081e-3 -2.164e-6 0 -74520 -50460];
delta_ws_final=[];
delta_meth_final=[];
for iii=1:6
delta_ws=G_H2(iii)+G_CO2(iii)-G_CO(iii)-G_H2O(iii);
delta_meth=G_CH4(iii)-G_C(iii)-2*G_H2(iii);
delta_ws_final=[delta_ws_final delta_ws];
```

```
delta_meth_final=[delta_meth_final delta_meth];
end
T_0=298.15;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
k1=exp(-((delta_meth_final(6)-
delta_meth_final(5))/(8.314*298.15)+(delta_meth_final(5)/(8.314*g_temp))...
+(int_eq_sp2(delta_meth_final,g_temp)/g_temp)-
int_eq_sp1(delta_meth_final,g_temp)));
k2=exp(-((delta_ws_final(6)-
delta_ws_final(5))/(8.314*298.15)+(delta_ws_final(5)/(8.314*g_temp))...
+(int_eq_sp2(delta_ws_final,g_temp)/g_temp)-
int_eq_sp1(delta_ws_final,g_temp)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%function for calculating int_eq_sp
function int_for_gibbs_difff1= int_eq_sp1(difff,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff1=difff(1).*log(tau)+((difff(2).*T_0+...
((difff(3)*T_0^2+(difff(4)/(tau^2.*T_0^2)))*((tau+1)/2)))*(tau-1));
end
function int_for_gibbs_difff2= int_eq_sp2(var_sp,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff2=var_sp(1).*T_0*(tau-1)+...
var_sp(2)*0.5*T_0^2*(tau^2-1)+var_sp(3)*T_0^3*(tau^3-1)/3+...
var_sp(4)*(tau-1)/(tau*T_0);
end
%k1=9.72e-02;k2=1.4561;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%finding lambda and gamma for below calculation%%%%%%%%%%%%%%%%%%%%%%%%
norm_1_C=ele_comp(1)/(12);
norm_1_H=ele_comp(2)/(1.008);
norm_1_O=ele_comp(3)/(16);
norm_1_N=ele_comp(4)/(14.007);
lambda=norm_1_H/norm_1_C;
gamma=norm_1_O/norm_1_C;
beta=norm_1_N/norm_1_C;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x0=xx0;
iter=1;
iter_m=1;
sol_final=[];
w=0;
Moisture_Content=[];
for N=1:length(w)
Moisture_Content=[Moisture_Content 18*100*w(N)/(24+18*w(N))];
end
Moisture_Content;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Main Loop for solving the equations of interests
for iter_m=1:length(w)
```

```
while(iter<=maxit)
y=-df1(x0)\f1(x0);
xn=x0+y;
err=max(abs(xn-x0));
if(err<=tol)
x=xn;
else
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x0=xn;
end
iter=iter+1;
end
iter=1;
sol_temp=x;
sol_final=[sol_final sol_temp];
iter_m=iter_m+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Multiplying m with 3.76 to get correct N2 mols
p=length(w);
frac_N2=[];
for l=1:p
frac_N2=[frac_N2 m*3.76];
end
final_comp=[sol_final(1:5,1:p);frac_N2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%fin_rep=input('Do you want to find syngas composition in dry syngas
basis(y/n): ','s');
fin_rep='n';
if fin_rep=='n';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas for each moisture content
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(final_comp(1:6,n))];
end
total_frac_m; %sum of all product gases
else
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas on dry basis for each moisture content
dry_final_comp=final_comp;
dry_final_comp(4,:)=[];
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(dry_final_comp(1:5,n))];
end
total_frac_m;
final_comp=dry_final_comp;
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%expressing all the components in molar fraction or volumetric fraction
final_frac_comp=[];
for MM=1:length(total_frac_m)
final_frac_m=[];
if fin_rep=='y'
l_in=length(xx0);
else
l_in=length(xx0)+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for NN=1:l_in
final_frac_m=[final_frac_m;final_comp(NN,MM)/total_frac_m(MM)];
end
final_frac_comp=[final_frac_comp final_frac_m];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function f=f1(X)
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);
val_1=x_2+x_3+x_5-1;
val_2=x_1+x_4+2*x_5-w(iter_m)-(lambda/2);
val_3=x_2+2*x_3+x_4-2*m-gamma-w(iter_m);
val_4=-k1*x_1^2+(x_5*(x_1+x_2+x_3+x_4+x_5+3.76*m));
val_5=x_2*x_4*k2-x_1*x_3;
f=[val_1; val_2;val_3;val_4;val_5];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function df=df1(X)
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);
df=[0,1,1,0,1;1 0 0 1 2; 0 1 2 1 0;-
2*x_1*k1+x_5,x_5,x_5,x_5,2*x_5+(x_1+x_2+x_3+x_4+3.76*m); -x_3 k2*x_4...
-x_1 k2*x_2 0];
end
end
```

APPENDIX C

SUPPLEMENTAL DATA FOR SELECTED FIGURES

Table C-1 Data for figures 3.1 and 3.3

Moisture content (weight %)	0	5.1140	9.7304	13.9184	17.7350	21.2276	24.4357	27.3927	30.1270	32.6629	35.0211	37.2197	39.2744	41.1989	43.0052
H_2	0.1735	0.1826	0.1904	0.1967	0.2018	0.2055	0.2081	0.2096	0.2102	0.2101	0.2093	0.2081	0.2065	0.2045	0.2023
CO	0.2395	0.2100	0.1830	0.1590	0.1379	0.1197	0.1043	0.0913	0.0804	0.0713	0.0637	0.0572	0.0517	0.0470	0.0429
CO_2	0.1143	0.1363	0.1560	0.1733	0.1882	0.2006	0.2107	0.2189	0.2253	0.2302	0.2341	0.2370	0.2391	0.2407	0.2418
CH_4	0.0401	0.0441	0.0474	0.0501	0.0520	0.0531	0.0536	0.0534	0.0528	0.0517	0.0505	0.0490	0.0473	0.0456	0.0439
3.76 N_2	0.4325	0.4271	0.4232	0.4209	0.4202	0.4210	0.4233	0.4268	0.4313	0.4366	0.4425	0.4488	0.4554	0.4622	0.4691
HHV (MJ/m3)	6.8275	6.7312	6.6218	6.5073	6.3821	6.2438	6.1028	5.9502	5.7966	5.6369	5.4832	5.3263	5.1689	5.0165	4.8691

Table C-2 Data for figures 3.2 and 3.4

Moisture content	0	4.7227	9.0194	12.9453	16.5464	19.8614	22.9231	25.7595	28.3945	30.8489	33.1406	35.2853	37.2967	39.1868	40.9663
H_2	0.1984	0.2034	0.2073	0.2100	0.2117	0.2126	0.2127	0.2122	0.2112	0.2098	0.2081	0.2061	0.2039	0.2015	0.1989
CO	0.1591	0.1385	0.1206	0.1053	0.0924	0.0815	0.0723	0.0646	0.0581	0.0525	0.0478	0.0437	0.0401	0.0369	0.0342
CO_2	0.1512	0.1661	0.1787	0.1891	0.1976	0.2045	0.2099	0.2142	0.2175	0.2201	0.2220	0.2235	0.2246	0.2254	0.2259
CH_4	0.0512	0.0532	0.0544	0.0550	0.0551	0.0546	0.0537	0.0525	0.0511	0.0496	0.0480	0.0463	0.0446	0.0428	0.0411
3.76 N_2	0.4401	0.4388	0.4390	0.4405	0.4432	0.4469	0.4514	0.4566	0.4621	0.4680	0.4742	0.4805	0.4869	0.4934	0.4998
HHV (MJ/m3)	6.5740	6.4578	6.3298	6.1954	6.0585	5.9128	5.7623	5.6111	5.4608	5.3126	5.1680	5.0232	4.8821	4.7395	4.6047

Table C-3 Data for figure 3.5

Equivalence ratio	0.16	0.18	0.2	0.22	0.24	0.26	0.28	0.3	0.32	0.34	0.36	0.38	0.4
H_2	0.2916	0.2777	0.2645	0.2520	0.2402	0.2290	0.2183	0.2080	0.1983	0.1890	0.1800	0.1714	0.1632
CO	0.4370	0.4117	0.3879	0.3658	0.3450	0.3254	0.3070	0.2897	0.2733	0.2579	0.2432	0.2293	0.2162
CO_2	-0.0023	0.0091	0.0198	0.0297	0.0390	0.0477	0.0559	0.0635	0.0707	0.0775	0.0839	0.0899	0.0956
CH_4	0.0083	0.0075	0.0068	0.0062	0.0056	0.0051	0.0046	0.0042	0.0038	0.0035	0.0031	0.0029	0.0026
$3.76N_2$	0.2665	0.2898	0.3117	0.3322	0.3516	0.3698	0.3869	0.4032	0.4186	0.4332	0.4471	0.4603	0.4728

Table C-4 Data for figure 3.6

Equivalence ratio	0.16	0.18	0.2	0.22	0.24	0.26	0.28	0.3	0.32	0.34	0.36	0.38	0.4
H_2	0.3432	0.3281	0.3137	0.3000	0.2870	0.2746	0.2628	0.2514	0.2406	0.2301	0.2201	0.2105	0.2012
CO	0.3646	0.3453	0.3270	0.3099	0.2938	0.2785	0.2641	0.2505	0.2375	0.2252	0.2136	0.2025	0.1919
CO_2	0.0242	0.0324	0.0401	0.0472	0.0540	0.0603	0.0663	0.0719	0.0772	0.0822	0.0869	0.0914	0.0957
CH_4	0.0114	0.0105	0.0096	0.0087	0.0080	0.0073	0.0067	0.0061	0.0056	0.0051	0.0047	0.0043	0.0039
$3.76N_2$	0.2408	0.2627	0.2833	0.3027	0.3210	0.3384	0.3549	0.3705	0.3854	0.3996	0.4131	0.4261	0.4384

Table C-5 Data for figures 3.7 and 3.9

Temperature (^{0}C)	600	700	800	900	1000	1100	1200
H_2	0.0570	0.1435	0.2102	0.2146	0.1914	0.1636	0.1368
CO	0.0034	0.0283	0.0804	0.1121	0.1248	0.1292	0.1286
CO_2	0.3552	0.3000	0.2253	0.1845	0.1671	0.1581	0.1533
CH_4	0.2520	0.1517	0.0528	0.0127	0.0030	0.0008	0.0002
3.76 N_2	0.3325	0.3765	0.4313	0.4762	0.5137	0.5483	0.5811
HHV (MJ/m3)	10.7998	8.2253	5.7966	4.6562	4.1341	3.7473	3.3739

Table C-6 Data for figures 3.8 and 3.9

Temperature (^{0}C)	600	700	800	900	1000	1100	1200
H_2	0.0378	0.1011	0.1680	0.2011	0.2081	0.2061	0.2021
CO	0.0709	0.1489	0.2280	0.2710	0.2896	0.2995	0.3062
CO_2	0.2443	0.1801	0.1153	0.0797	0.0636	0.0545	0.0480
CH_4	0.1348	0.0874	0.0384	0.0128	0.0042	0.0016	0.0007
3.76 N_2	0.5076	0.4697	0.4305	0.4101	0.4032	0.4011	0.4003
HHV (MJ/m3)	6.7407	6.6447	6.5448	6.4901	6.4715	6.4672	6.4648

Table C-7 Data for figure 4.6

Moisture Content	12	14	16	20
Hydrogen (H_2)	14.32	15.94	19.23	16.84
Carbon monoxide (CO)	11.4	10.6	13.75	8.1
Carbon dioxide (CO_2)	13.65	14.89	15.54	18.61

Table C-8 Data for figure 4.7

Moisture Content	12	14	16	20
Syngas flow (Avg) (m/s)	2.376	2.716	3.661	2.63

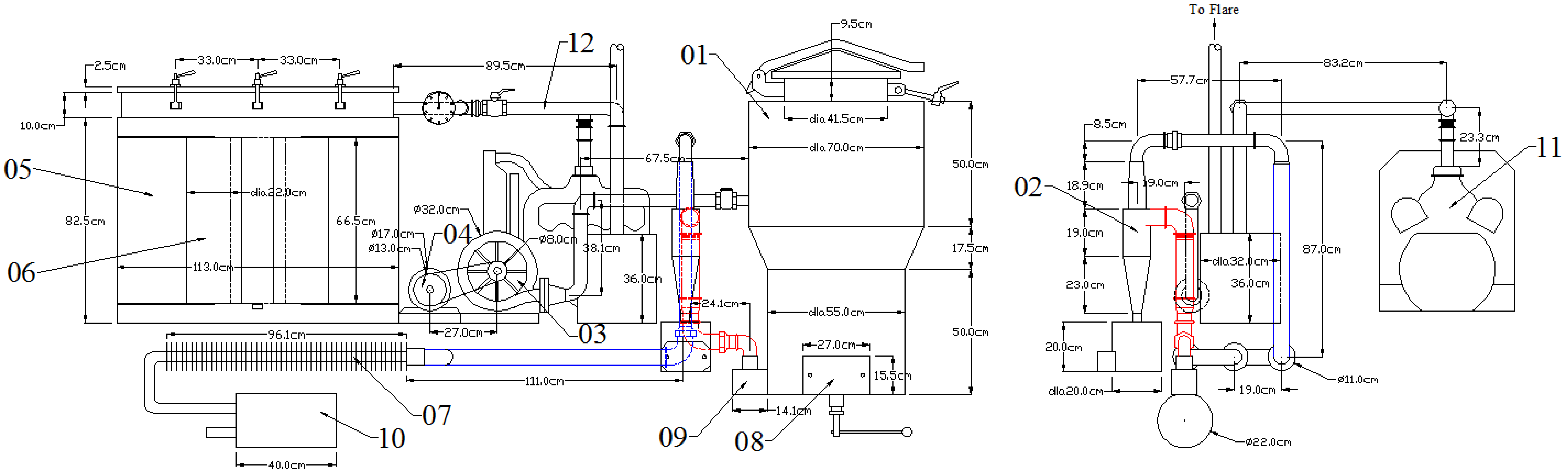
Table C-9 Data for figure 4.8 and 4.9

Time	Syngas flow (m/s)	Syngas Temp	Pyrolysis temp	Flame property
12:30	2.18-1.34 (1.76)	80		
12:50	2.04-1.37 (1.705)	140	35.2	
13:05	2.24-1.53 (1.885)	176	86	good
13:35*	2.25-1.55 (1.9)	180	173	Good
13:55	2.17-1.46(1.815)	180	244	Good
14:15	2.36-1.74 (2.05)	196	236.8	good
14:55*	2.49-1.73 (2.11)	218	130.8	Good
15:30	2.52-1.71 (2.115)	152	177.2	Good
16:00	2.34-1.55 (1.945)	120	197	bad
16:15*	2.57-164 (2.105)	110	133.8	bad
16:30	2.73-1.64 (2.185)	110	128.8	Good

Remark: (*) sign denotes the times at which the feedstock inside the gasifier redistributed manually.

APPENDIX D

ASSEMBLY DRAWING OF THE EXPERIMETNAL SETUP



Part No.	Part Name	Part No.	Part Name
01	Gasifier (Reactor)	07	Finned Condenser
02	Cyclone Separator	08	Ash Collector
03	Centrifugal Blower	09	Syngas Outlet
04	DC Motor	10	Condensate removal
05	Gas Tank (Square)	11	IC Engine
06	Cloth filter	12	Gas Pipe

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