Study on Characteristics of Syngas Derived From Various Biomasses

By

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Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
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Approved by,

(Ir. Dr. Shaharin Anwar Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS

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July 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD FADHIL BIN HAJI KARIM

ABSTRACT

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, biofuel, or biomass, into carbon monoxide and hydrogen by reaction of the raw material at high temperatures with a controlled amount of oxygen and/or steam. Presently, there are many biomass sources available for gasification. Although there is an abundant choice of biomass, the challenge that we are currently facing is that there is not one single universal gasifier that is capable of producing syngas from different types of biomass. In present technology, the design of gasifier is very fuel-specific which means each gasifier utilizes one type of primary biomass source. Should there is an interruption or inconsistency of the primary biomass source; it would be beneficial if the option of replacing it with another alternative existed. Thus, this project aims to identify which different types of biomass sources can be gasified in one single gasifier. The downdraft gasifier was designed to have oil palm fronds as its primary feedstock. The objective was to see what feedstock is compatible to oil palm fronds using the same downdraft gasifier. This study was conducted using locally available biomass sources which are oil palm fronds, woods, coconut husks and sugarcane bagasse. Prior to the experiment, three chemical analysis were being carried out, proximate, ultimate and energy analysis for each feedstock. Afterwards, gasification experiment would be conducted for each feedstock individually. The resulting temperature profile, syngas analysis and problems occurred during gasification were recorded. Besides that, a simulation to determine the syngas composition was carried out using Engineering Equation Solver (EES). Looking at the results, in a nutshell, woods were the most promising replacement for oil palm fronds. It has the highest energy content at 22292J/g and at 11% moisture content (wet basis), the gasification experiment produced syngas with no gasification problem and little tar formation. The syngas produced contained 13.87% carbon monoxide, 51.69% hydrogen, 31.99% carbon dioxide and 2.46% methane.

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INTRODUCTION

1.1 Background Study

As time goes by, the demand for energy in Malaysia is increasing exponentially. The amount of energy consumption is estimated to spike up to 100 Million Tonnes of Oil Equivalent by 2030 (Shuit, 2008).

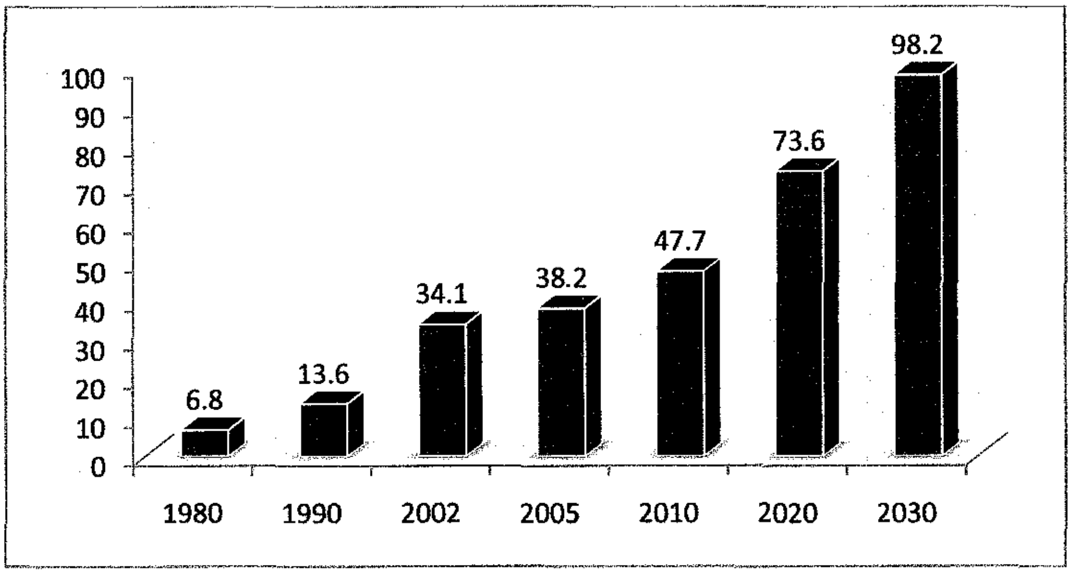


Figure 1.1: Energy demand in Malaysia (Shuit, 2008)

In order to meet the increasing demand of energy, many researches have been done to look for some alternative energy to assist or possibly replace crude oil. Among all of the alternative energy available, there is one particularly that has not been fully developed and it is still on a learning curve. The energy mentioned is the biomass energy especially the syngas through biomass gasification process.

Biomass can be defined as biological material derived from living or recently living organism such as wood, tree trunks, and dead leaves. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material. In terms of chemical composition, biomass is carbon based and is composed of a mixture of organic molecules containing hydrogen usually including atoms of oxygen, often nitrogen and also small quantities of other atoms, including alkali, alkaline earth and heavy metals.

There are five basic categories of biomass source (Biomass Energy Centre Malaysia):

- **Virgin wood**: from forestry, arboriculture activities or from wood processing
- **Energy crops**: high yield crops grown specifically for energy applications
- **Agricultural residues**: residues from agriculture harvesting or processing
- **Food waste**: from food and drink manufacture, preparation and processing, and post-consumer waste
- **Industrial waste and co products**: from manufacturing and industrial processes

The energy content which is the fixed carbon of biomass can be exploited by direct combustion or after conversion and eventual upgrading into a more valuable fuel by physical, biological or thermo chemical processes. In Table 1.1 and Figure 1.2, the main characteristic of thermo chemical conversion processes and products is presented:

Table 1.1: Thermo chemical conversion technologies and products (Ferrero, 2009)

Technology	**Primary Product**	**Applications**
Pyrolysis	Gas Liquid Solid char	Fuel gas Oil or liquid fuel substitution Solid fuel or slurry fuel
Flash pyrolysis	Liquid	Oil or liquid fuel substitution
Slow pyrolysis	Solid char	Solid fuel or slurry fuel
Liquefaction	Liquid	Oil or liquid fuel substitution
Gasification	Gas	Fuel gas
Combustion	Heat	Heating

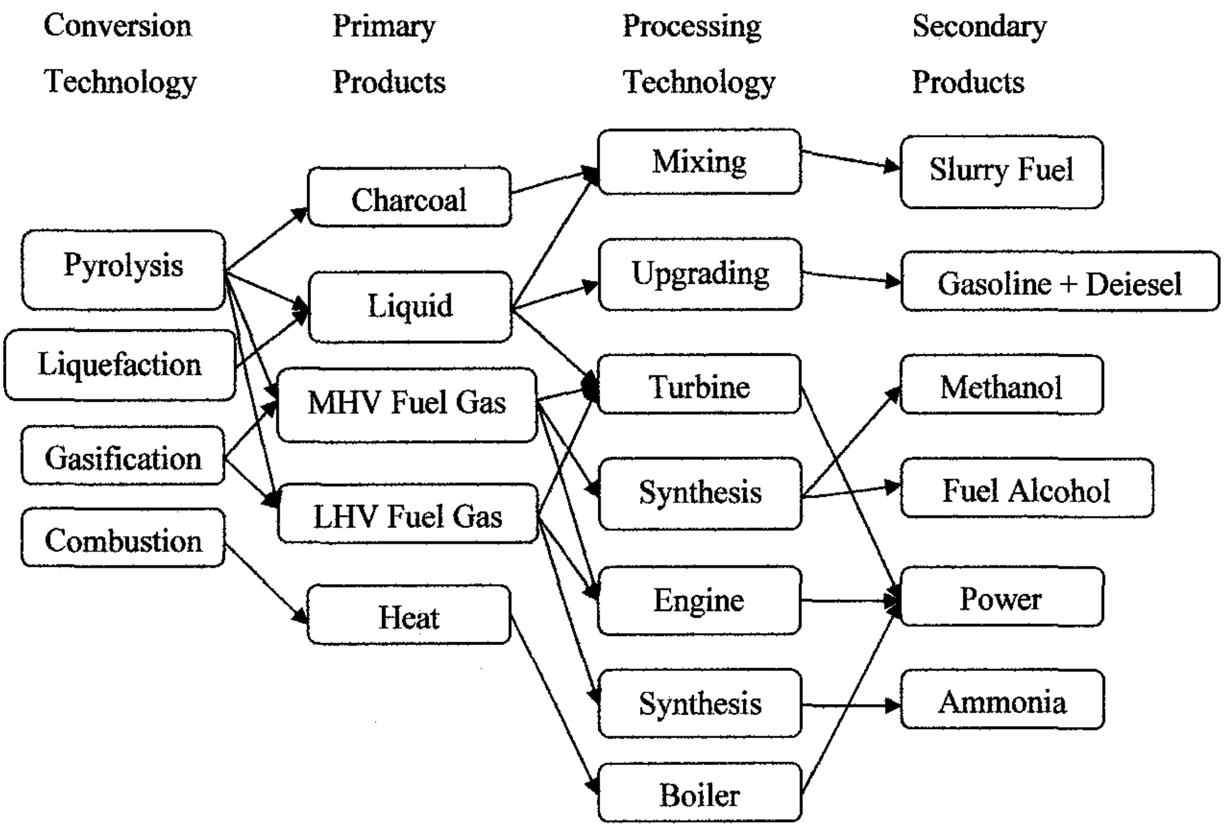


Figure 1.2: Primary and secondary products from thermo chemical biomass processing (Grassi, 2009)

Typically, in the complete combustion of biomass with excess supply of oxygen, carbon dioxide and water in the form of steam are form. The simplified equations of complete biomass combustion are as follow:

$$C + O_2 \longrightarrow CO_2$$

$$2H + O_2 \longrightarrow 2H_2O$$

However, gasification is achieved in the presence of heat and a limited supply of oxygen resulting in incomplete combustion of the feed material. By definition, gasification process is the incomplete combustion of biomass at approximately 1000°C resulting in the production of synthetic gas consisting of carbon monoxide (CO), nitrogen (N_2), hydrogen (H_2) and traces of methane (CH_4) (Rajvanshi, 1986). The reactor where the gasification takes place is called the gasifier. The simplified gasification reaction is as follows:

$$CH_{1.4}O_{0.6} + 0.2\ O_2 \rightarrow CO + 0.7\ H_2$$

The resulting syngas from gasification can be utilized to several applications. One of the most attractive uses of producer gas is its use in internal combustion engines for the production of shaft power which in turn can be used for generating electricity, pumping water, milling rice, running compressors, motive power etc. Besides that, syngas can also be directly combusted in external combustion systems such as boilers, kilns, driers, ovens etc.

1.2 Problem Statement

During World War 2, the gasifier used specially prepared $1 \times 2 \times 2$ cm^3 hardwood blocks. However, these blocks are only a small portion of biomass available in the world. There are many others that have bigger calorific value and potential to be developed as feedstock.

Although the potential of biomass seems vast, there is some setback in the gasifier design. In present technology, there is not a single universal gasifier that is capable of producing syngas from all types of biomass. This is because biomass exists in a wide variety of forms, making it necessary to tailor the shapes of the gasifier to each form (Rajvanshi, 1986).

Furthermore, almost all of the existing biomass contain more than 80% of volatile matter and can be expected to have unique problems such as severe tar formation until proven otherwise. Therefore, the resulting gasifier design must be very fuel specific. Although there is an abundant of choice for biomass in Malaysia, it can be concluded that various different biomass require various different types of gasifier and operating conditions.

Looking at the current issue, although one design of gasifier may not be suitable for all types of biomass source, it would be beneficial if the source of biomass can be diversified to overcome inconsistency or interruption of the primary biomass source. This study is required in determining the compatibility of various different biomass sources.

1.3 Objectives and Scope of Study

This project aims to identify which different types of biomass sources can be gasified in one single gasifier. The downdraft gasifier was designed to have oil palm fronds as its primary feedstock. The objective is to see what feedstock is compatible to oil palm fronds using the same downdraft gasifier and it can be achieved through:

- Thermo-chemical analysis of the biomass feedstock such as ultimate analysis, proximate analysis and energy content analysis to deduce the compatibility of each biomass with oil palm fronds.
- Gasification of oil palm fronds and each selected feedstock to see and compare the result of syngas emission.

The scope of this study will include biomass sources that are easily accessible in Malaysia. Furthermore, the study is based on only one designated downdraft gasifier.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Basic Concept of Gasification and Gasifier

Gasification is most simply thought of as a process of staged or choked combustion. It is burning solid fuels like wood or coal without enough air to complete combustion, so the output gas still has combustion potential. The gas produced by this method goes by a variety of names: wood gas, syngas, producer gas, town gas, and others.

The input to gasification is some form of solid carbonaceous material– typically biomass or coal. All organic carbonaceous material is made up of carbon C, hydrogen H, an oxygen O atom in variety of molecular forms. The goal in gasification is to break down this wide variety of forms into the simple fuel gasses of H_2 and CO– hydrogen and carbon monoxide.

Proper gasification is a bit more complicated than just the choked combustion summary above. It is actually a series of distinct thermal events put together so as to purposely convert solid organic matter into specific hydrocarbon gasses as output. The goal in gasification is to take control of the discrete thermal processes usually mixed together in combustion, and reorganize them towards desired end products.

Gasification is made up for four discrete thermal processes: **Drying, Pyrolysis, Combustion and Reduction**. All four of these processes are naturally present in the flame you see burning off a match, though they mix in a manner that renders them invisible to eyes not yet initiated into the mysteries of gasification. Gasification is merely the technology to pull apart and isolate these separate processes, so that it might interrupt the fire and pipe the resulting gasses elsewhere.

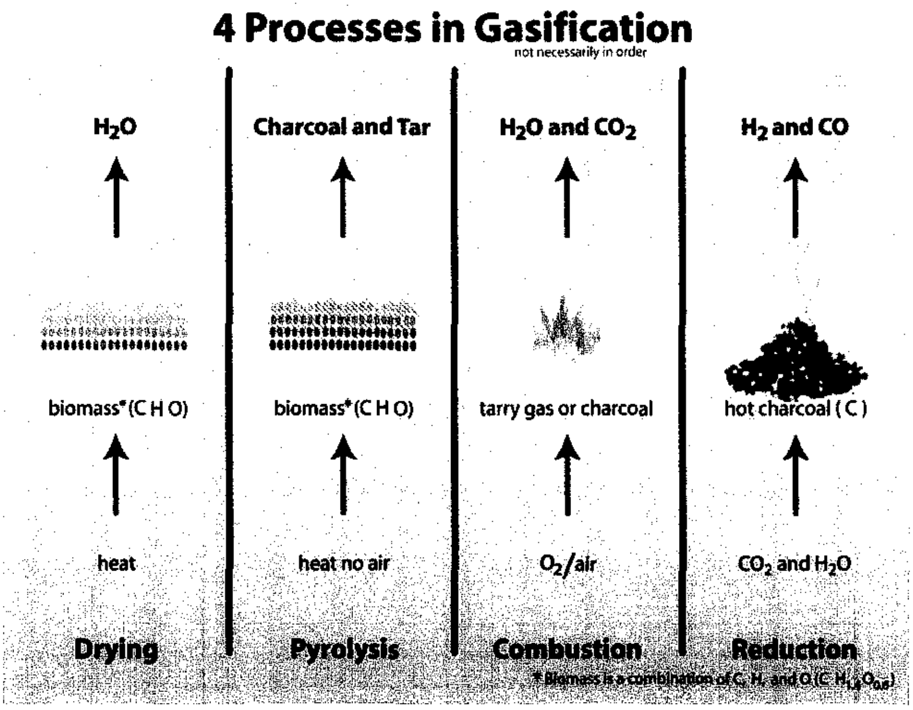


Figure 2.1: Four processes in gasification (Fischer, 2009)

Pyrolysis

Pyrolysis is the application of heat to raw biomass, in an absence of air, so as to break it down into charcoal and various tar gasses and liquids. Biomass begins to "fast decompose" with once its temperature rises above around 240°C. The biomass breaks down into a combination of solids, liquids and gasses. The solids that remain are commonly call charcoal. The gasses and liquids that are released are collectively called tars.

The gasses and liquids produced during lower temperature pyrolysis are simply fragments of the original biomass that break off with heat. These fragments are the more complicated H, C and O molecules in the biomass that are commonly refered to as volatiles. As the name suggests, volatiles are reactive and are less strongly bonded in the biomass than the fixed carbon, which is the direct C to C bond. Thus in review, pyrolysis is the application of heat to biomass in the absence of air/oxygen. The volatiles in the biomass are evaporated off as tars, and the fixed carbon-to-carbon chains are what remains– otherwise known as charcoal.

Reduction

Reduction is the process stripping of oxygen atoms off completely combusted hydrocarbon molecules, so as to return the molecules to forms that can burn again. Reduction is the direct reverse process of combustion. Combustion is the combination of an HC molecule with oxygen to release heat. Reduction is the removal of oxygen from an HC molecule by adding heat. Combustion and reduction are equal and opposite reactions. In fact, in most burning environments, they are both operating simultaneously, in some form of dynamic equilibrium, with repeated movement back and forth between the two states.

Reduction in a gasifier is accomplished by passing carbon dioxide CO_2 or water vapor H_2O across a bed of red hot char C. The hot char is highly reactive with oxygen, and thus strips the oxygen off the gasses, and redistributes it to as many single bond sites as possible. The oxygen is more attracted to the bond site on the C than to itself, thus no free oxygen can survive in its usual diatomic O_2 form. All available oxygen will bond to available C sites as individual O, until all the oxygen is gone. When all the available oxygen is redistributed as single atoms, reduction stops. Through this process, CO_2 is reduced to CO and H_2O is reduced to H_2 and CO. Combustion products become fuel gasses again.

Combustion and Drying:

These are the most easily understood of the four processes of gasification. Combustion is what generates the heat to run reduction, as well as the CO_2 and H_2 to be reduced in reduction. Combustion can be fueled by either the tar gasses or char from pyrolysis. Different reactor types use one or the other or both.

In a downdraft gasifier, burning of the tar gasses from pyrolysis generates heat to run reduction, as well as the CO_2 and H_2O to reduce in reduction. The goal in combustion in a downdraft is to get good mixing and high temperatures so that all the tars are either burned or cracked, and thus will not be present in the outgoing gas. The char bed and reduction contribute a relatively little to the conversion of messy tars to useful fuel

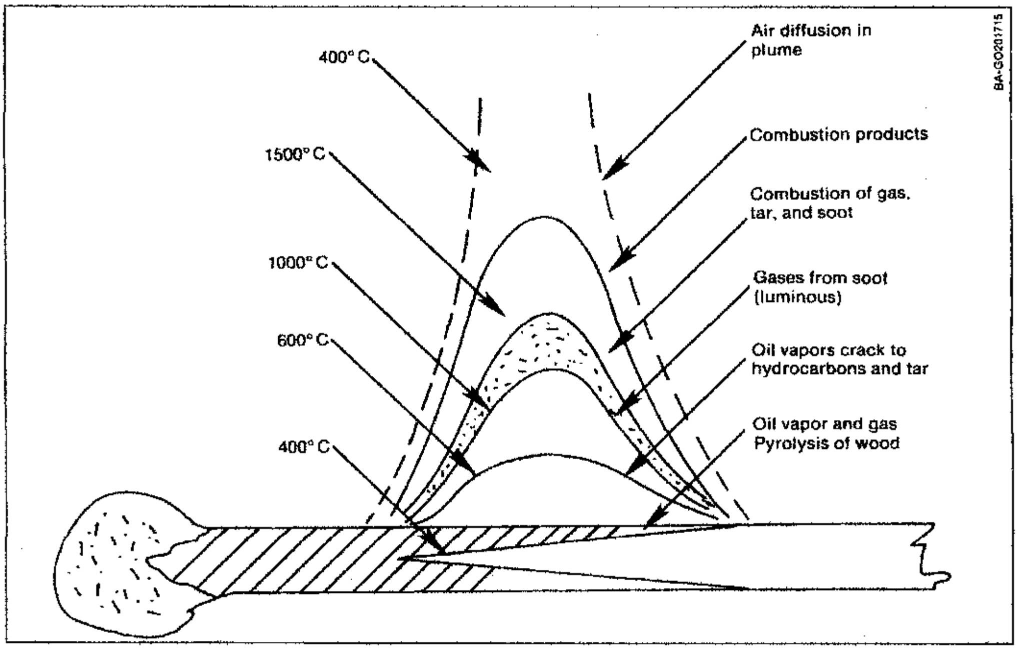


Figure 2.3 Pyrolysis, gasification and combustion in the flaming match (Solar Energy Research Institute, 1989)

2.2 Types of Gasifier

In the practical realization of gasification processes a broad range of reactor types has been and continues to be used. For most purposes, these reactor types can be grouped into one of three categories: fixed bed gasifiers, fluid-bed gasifiers, and entrained-flow gasifiers. (Higman, 2003)

Fixed-bed gasifiers are characterized by a bed in which the coal moves slowly downward under gravity as it is gasified by a blast that is generally in a counter-current blast to the coal. In such a counter-current arrangement, the hot synthesis gas from the gasification zone is used to preheat and pyrolyse the downward flowing coal. With this process the oxygen consumption is very low, but pyrolysis products are present in the product synthesis gas. The outlet temperature of the synthesis gas is generally low, even if high, slagging temperatures are reached in the heart of the bed. Moving-bed processes operate on lump coal. An excessive amount of fines can block the passage of the up-flowing syngas.

For this research, the primary focus is on fixed-bed gasifier. There are 3 sub categories underneath fixed-bed gasifiers which are: Downdraft, Updraft and Crossdraft. As the name implies, the updraft gasifier has air passing the biomass from the bottom and the combustible gas comes out from the top of the gasifier; whereas for the downdraft gasifier, the air intake is at the top of the gasifier and the syngas is emitted at the bottom.

Each gasifier has their own pros and cons adjacent to the biomass fuel that is used (Rajvanshi, 1986). Table 2.1 shows all the advantages and disadvantages of each gasifier design.

Table 2.1: Advantages and disadvantages of each gasifier design (Goswani, 1986)

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

2.3 Cyclone Gasifier Design & Operation

Design and operation of the cyclone gasifier was earlier studied and published by a researcher named Fredriksson (1999). The mentioned gasifier design and operation is closely related to this study.

Cyclone gasification system is a process intensified system acting as a gasifier to generate combustible gases and also as a gas cleaner to separate unburned particles from the gas flow (Fredriksson, 1999). Generally other gasification systems which deal with small particles as fuels needed a cyclone separator to remove large particles. However, this separator is unnecessary as cyclone gasification system can be operated entirely as a single unit.

In utilizing various biomass fuels, cyclone gasification system has more edge compared to other conventional gasification systems. Cyclone gasifier is capable of gasifying smaller size particles of less than 1 mm in diameter directly into the gasification system without needing extra pretreatment on the fuels and the reaction may take place at atmospheric pressure (Fredriksson, 1999).

Besides that, cyclone gasifier also operates at a relatively moderate temperature. Therefore the volatile matters will be released and the fixed carbon will be gasified without having to face problems such as ash melting or ash vaporization. The corrosive ash will remain as solid in char particles which will be then collected in the ash bin. A schematic of the gasification utilized by Fredriksson's study is shown in Figure 2.4.

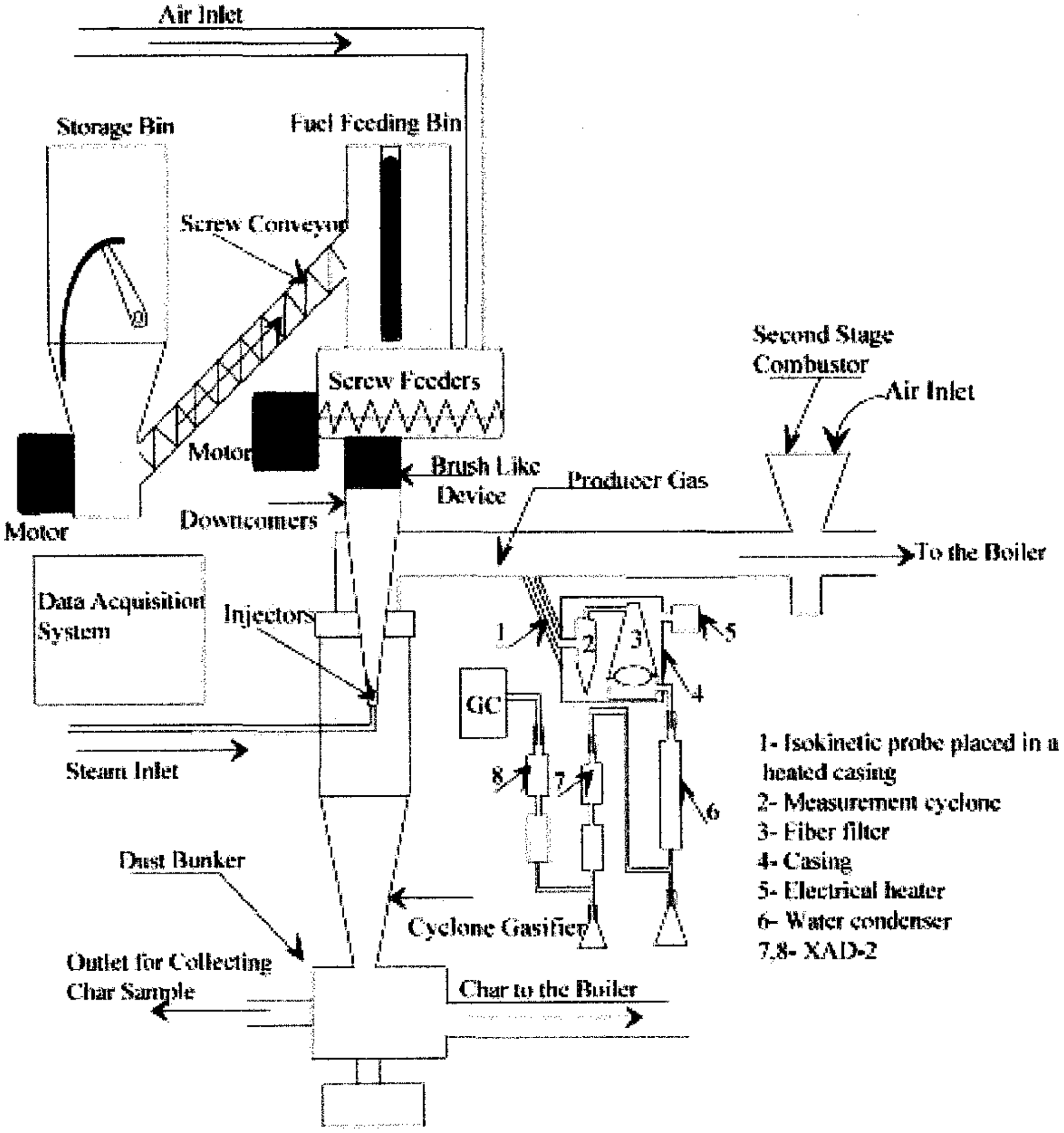


Figure 2.4: Schematic of a two stage atmospheric gasification (Fredriksson, 1999)

2.4 Biomass Properties

There is an abundant choice of biomass in the world. Shown in Table 2.2 is the general type of biomass properties. The biggest potential biomass in terms of high heating value is the charcoal at 25-32 MJ/kg. The least potential biomass is the palm oil residues (fruit stems) at the HHV value of 5 MJ/kg.

Table 2.2: Various biomass properties (Quaak, 1999; Arbon, 2002)

Biomass	**HHV (MJ/kg)**	**Moisture (wt%)**	**Ash (wt%)**	**Sulfur (wt% dry)**	**Chlorine (wt% dry)**
Charcoal	25–32	1–10	0.5–6		
Wood	10–20	10–60	0.25–1.7	0.01	0.01
Coconut shell	18–19	8–10	1–4		
Straw	14–16	10	4–5	0.07	0.49
Ground nut shells	17	2–3	10		
Coffee husks	16	10	0.6		
Cotton residues (stalks)	16	10–20	0.1		
Cocoa husks	13–16	7–9	7–14		
Palm oil residues (shells)	15	15			
Rice husk	13–14	9–15	15–20		
Soya straw	15–16	8–9	5–6		
Cotton residue (gin trash)	14	9	12		
Maize (stalk)	13–15	10–20	2 (3–7)	0.05	1.48
Palm oil residues (fibres)	11	40			
Sawdust	11	35	2		
Bagasse	8–10	40–60	1–4		
Palm oil residues (fruit stems)	5	63	5		
Bark				0.07	0.49

Derived from Quaak *et al.*, 1999; Arbon, 2002.

Table 2.3: Proximate and ultimate analysis of typical biomass (Klentsch, 2001)

Proximate analysis			**Ultimate analysis**	
Volatile matter	wt% maf	>70	C, wt%	54.7
Ash	wt% ar	1.5	H, wt%	6.0
Moisture	wt% ar	20	O, wt%	38.9
Fixed carbon	wt% ar	<15	N, wt%	0.3
			S, wt%	0.1

With reference to the PhD dissertation by Klentsch from Engler-Bunte-Institut der Universität Karlsruhe (TH), Table 2.3 lists the typical results of biomass for proximate and ultimate analysis. In the proximate analysis, the volatile matter is more than 70 wt%, ash at 1.5 wt%, moisture at 20 wt% and fixed carbon less than 15 wt%.

As for the ultimate analysis, it can be seen than carbon constitutes the most in the chemical composition of the biomass at 54.7wt%. Oxygen comes secondly at 38.9 wt%, hydrogen at 6 wt%, nitrogen at 0.3 wt% and lastly sulphur at 0.1 wt%.

CHAPTER 3

METHODOLOGY

3.1 Project Flow

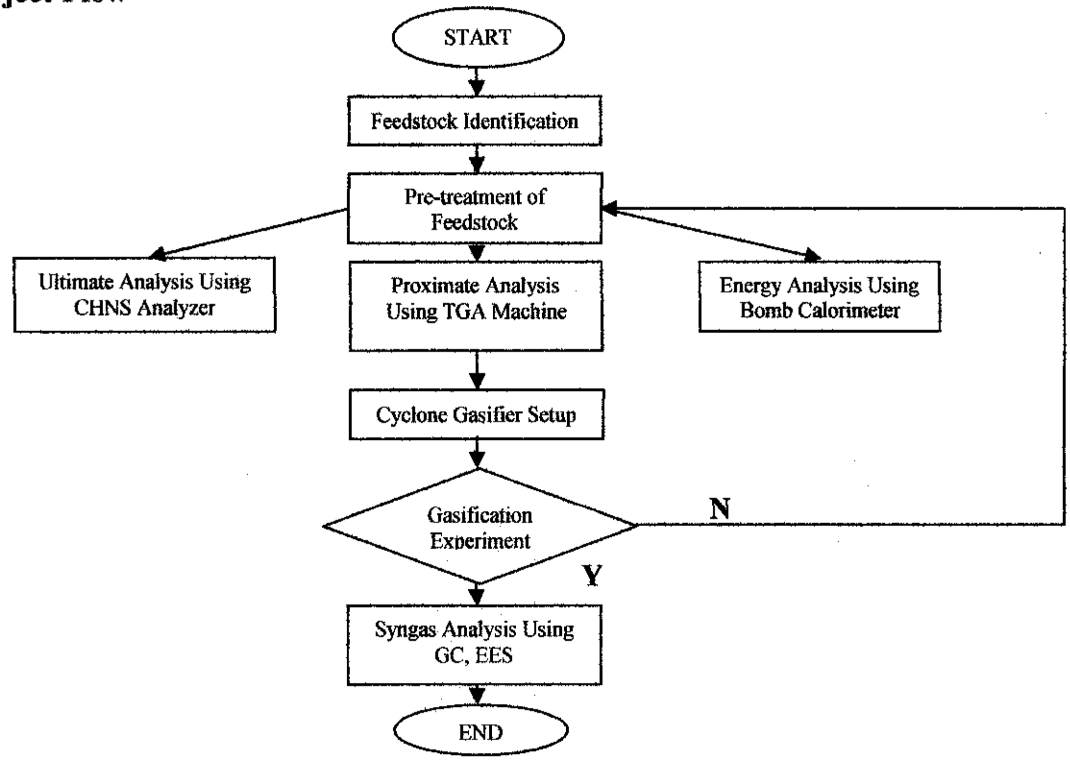


Figure 3.1: Project flow chart

Figure 3.1 shows the project flow chart and the first step is to choose four types of biomasses according to several key factors. For the first half of the study, thermo-chemical analysis of all the biomasses harvested would be investigated by means of Calorific Test using bomb calorimeter and Ultimate Analysis using CHNS Analyzer. Afterwards, gasification experiment would be carried out for three types of feedstock. The resulting syngas would be analyzed using GC machine and the gasification results would be observed and recorded.

For the second half of the study, Proximate Analysis using TGA machine and gasification experiment would also be carried out for the remaining feedstock. Besides that, syngas composition from all biomass gasification would be simulated using engineering equation solver (EES).

3.2 Gantt Chart

Figure 3.2 shows the Gantt charts for this project. The project time is divided into two as mentioned previously. The purpose of these charts is to assist in keeping the work schedule in check so that any possible delays can be prevented.

Final Year Project 1 July 2010																
No.	Detail/ Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14
1	Journal Study & Literature Review	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨
2	Gasifier Concept Familiarization	▨	▨	▨												
3	Identification & Harvestation of Feedstock			▨	▨				▨	▨						
4	Preparation of Feedstock & Drying Process			▨	▨				▨	▨						
5	Submission of Preliminary Report				▨											
6	Energy and Ultimate Analysis				▨	▨	▨									
7	Gasifier Equipment Setup				▨											
8	Gasification Experiment of OPF, Sugarcane and Woods						▨		▨	▨	▨	▨	▨			
9	Submission of Progress Report 1									▨						
10	Gasification Result Analysis								▨	▨	▨	▨	▨	▨	▨	
11	Submission of Interim Final Report Draft															▨

Final Year Project 2 Jan 2011																
No.	Detail/ Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14
1	Journal Study & Literature Review	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨
2	Identification & Harvestation of Feedstock	▨	▨													
3	Preparation of Feedstock & Drying Process		▨	▨												
4	Proximate Analysis			▨	▨	▨										
5	Gasification Experiment of Coconut Husks						▨		▨	▨	▨	▨				
6	Submission of Progress Report 2									▨						
7	Syngas Simulation Using EES										▨	▨	▨			
8	Submission of Draft Report													▨		
9	Submission of Softbound Dissertation & Technical Report														▨	
10	Oral Presentation															▨
11	Submission of Hardbound Dissertation															▨

Figure 3.2: Gantt charts

3.3 Feedstock Identification & Pre-treatment

The first step in this study is to identify which of the biomass sources available locally will be used in the gasification experiment. Table 3.1 shows the four major factors that are being considered for this experiment and they are the economic factor, availability factor, transportation cost and energy content. Each type of biomass is being assigned a weight from 1-10 for the respective factor, 1 being least appealing, 10 being most appealing. The biomass with the highest overall score would be selected and harvested.

Table 3.1: Biomass fuel identification

Types of Biomass	Economic Factor	Availability Factor	Transportation Cost	Energy Content	Overall Score
1)Woods	Price is reasonable. Weight: 7	Vast Weight:10	Distance is more than 20 km Weight: 6	Approximately 20 MJ/kg Weight: 10	33
2)Sugarcane Bagasse	Relatively cheap/ Can be obtained free of charge Weight: 10	Available at the bazaar Weight: 7	Bazaar is approximately 2~3 km Weight: 10	Approximately 10 MJ/kg Weight: 6	33
3)Coconut Shell and Husks	Relatively cheap/ can be obtained free of charge Weight: 10	Vast Weight: 10	Distance is more than 20 km Weight: 6	Approximately 19 MJ/kg Weight: 9	35
4)Empty Fruit Bunch	Quite expensive as it is only available in large quantity up to 5-10 tonnes Weight: 3	Vast as UTP is situated near many oil palm plantation Weight: 10	Plantation is approximately 2~3 km Weight: 10	Approximately 18 MJ/kg Weight: 8	31
5)Rice Husk	Price is reasonable Weight 4	Limited resources Weight: 4	Distance is more than 30 km Weight: 5	Approximately 14 MJ/kg Weight: 7	20

Ultimately, the biomass sources that have the highest score are selected for this experiment as shown in Figure 3.3 to 3.5. They are:

1. Oil palm fronds (primary source, virgin woods)
2. Sugarcane bagasse (agricultural residue)
3. Woods (virgin woods)
4. Coconut shell and husks (agricultural residue)

Figure 3.3: Oil palm fronds

Figure 3.4: Sugarcane bagasse

Figure 3.5: Woods

Figure 3.6: Coconut husks

Next, the feed stock underwent pre-treatment such as cutting process to achieve appropriate sample size. The particle size of biomass fuel and the size distribution is an important parameter. It affects the pressure drop across the gasifier and power output produced from the gasification process. Large pressure drops reduces the particle separation in the cyclone attachment, resulting in low temperature inside the gasifier chamber. Theoretically, smaller biomass fuel means faster gasification reaction.

Adjacent to the hopper design of the designated gasifier, the shape of the woods and OPF were reduced to 1-2 inch using axe, blade and grinder (Model: KEN 4210, Shanghai KEN Tools, 220V, 50Hz, 1200W). An alternative to this would be to use a pallet machine. A pallet machine can produce a more standardized product. As for the sugarcane bagasse and coconut husks, the shapes are quite hard to alter, due to its broom-like extremities and fibrous nature. Both of them did not underwent any cutting process.


a) Woods b) Oil palm fronds

Figure 3.7: Woods and OPF after cutting

The feedstock were then left to dry under the sun for a period of one week. This process is necessary to reduce the moisture content of the sample. Fuel with moisture content above about 30% makes ignition difficult and reduces the CV of the product gas due to the need to evaporate the additional moisture before combustion/gasification can occur (Mckendry, 2001). High moisture content reduces the temperature achieved in the oxidation zone resulting in the incomplete cracking of the hydrocarbons released from the pyrolysis zone.

The dried feedstock were then underwent first stage of grinding to prepare it in powder form using a Granulator. The granulated samples were then turned into its powdery form using a Rock Lab Grinder. The fine powder forms of sample were used in the ultimate, proximate and energy analysis which will be discussed in Chapter 4.

3.4 Thermo-Chemical Analysis

Chemical analysis is necessary to justify the feasibility of using biomass in a gasification system. Besides that, by conducting the chemical analysis, the properties of each feedstock can be compared to oil palm fronds. This comparison will help in deducing an early hypothesis of which biomass works well with oil palm fronds in the designated downdraft gasifier. In the present work, the chemical analysis included Energy Analysis, Ultimate Analysis and Proximate Analysis. Each of the analysis would be discussed in the following sections.

3.4.1 Energy Analysis

To determine the amount of energy stored in the feedstock, an energy analysis was conducted using the IKA C-5000 Bomb Calorimter which is shown in Figure 3.8. High Heating Value or HHV of a fuel specimen is the heat produced by reaction of fuel with oxygen in a bomb calorimeter and measuring the heat released to a known quantity of water. The heat released during this procedure represents the maximum amount of energy that can be obtained from combusting the fuel.

Figure 3.8: The IKA C-5000 bomb calorimeter

The parameter for the calorific test was done according to ASTM D 5865-07, Standard test Method for Gross Calorific Value of Coal and Coke. The test would be a judging parameter on the suitability or potential of each biomass feed by means of comparing the value of data obtained against the predetermined existing data of various biomass resources.

Theoretically, the value of HHV can be obtained through these two equations:

- HHV (MJ/kg) = $33.86C+144.4(H-O/8)+9.428S$, Dulong Formula (Perry & Chelton, 1973)

- HHV (MJ/kg)= $34.91C+117.83H-10.34O-1.51N+10.05S-2.11Ash$ (Chaniwala & Parikh, 2002)

However, both of these equations require the chemical composition of the feedstock through ultimate analysis using CHNS analyzer. A set of five runs were conducted to determine the average energy value contained in the feedstock in units of J/g.

3.4.2 Ultimate Analysis

The purpose of preparing a fine dry powder sample previously is to analyze the chemical compositions of fuel. The ultimate analysis or CHNS test was carried out using the Leco CHNS-932 machine. The CHNS machine works based on the principle that high temperature combustion is used as the means of removing the elements from the material. This analysis will report the carbon, hydrogen, nitrogen, and sulphur content in the fuel samples. The parameter for ultimate analysis was set according to ASTM D 3176-89. The weight that was used for the test was approximately one mg in the form of fine powder. A set of six runs were conducted to obtain an average value of carbon, hydrogen, nitrogen and sulphur composition in the sample. Besides these four elements, the remaining weight percentage can be assumed to be oxygen content.

High carbon content would highlight the possibility of the feedstock to become a fuel source for the gasification process. Low sulphur content would portray the potential of the feedstock as an environmental friendly renewable energy source as sulphur would react with water, oxygen and oxidants to form acidic compound as found in acid rains.

3.4.3 Proximate Analysis

Proximate analysis was carried out to determine the percentage of moisture, volatile matter, fixed carbon and ashes in each fuel. Proximate analysis is an empirical technique in which the mass of substance is heated at a controlled rate and the mass loss is recorded as a function of time. The parameter of TGA analysis were set based on ASTM

E 1131-98, Standard Test Method for Compositional Analysis by Thermogravimetry. The equipment used was the Perkins Elmer Pyris TGA-7 as shown in Figure 3.9. The basic principle of a TGA analysis module is to record mass loss during programmed time or temperature profile. Changes in mass indicate moisture loss and phase changes which occur at set temperature indicative of the compound.

High content of ash in a biomass feed can cause a variety of problems in the gasification process. Slagging formation in the gasifier, caused by melting and agglomeration of ashes will greatly add to the amount of labor required to operate the gasifier. Slagging can even lead to excessive tar formation and/or complete blocking of the reactor. Slagging is expected for fuels having ash contents of 12% (Osorio, 2005) or above and this is an indication for extra caution required during gasification.

The volatile matter content is a measure of the reactivity of a fuel to the gasification process. Biomass generally has higher volatile matter content than conventional fossil fuel such as coal and this is a good indicator on the performance of the biomass fuel in a gasifier. Most biomass contains an average of 80% volatile matter. (Renew 2004).

The fixed carbon content is the mass remaining after the releases of volatiles, excluding the ash and moisture contents. Average value for fixed carbon for a biomass fuel is 21.1% (Renew, 2004).The significant of volatile matter and fixed carbon content is that they provide a measure of ease in which the biomass fuel can be ignited and subsequently gasified of oxidized, depending on how the biomass is utilized as an energy source. For this study, three samples of each feedstock underwent the TGA Analysis and the average moisture, ash, volatile matter and fixed carbon content were recorded.

The fractions determined through such an analysis are as follows:

- Moisture, which is obtained by maintaining a sample of solid fuel within an inert atmosphere at 378 K and near ambient pressure until no variation of its mass is detected. The moisture content on a wet basis is given by the ratio between the mass lost by the sample and its original mass.

- Volatile content, which is found by maintaining the sample in an inert atmosphere at around 1300 K until no variation of its mass is detected. The volatile content at wet basis is given by the ratio between the lost mass and the original mass (before drying) of the sample.
- Fixed carbon fraction, which is revealed by reacting the devolatillized sample with oxygen until no mass variation is detected. The fixed carbon content at wet basis is expressed by the ratio between the mass loss during the combustion and the sample original mass.
- Ash content at wet basis is given by the ratio between residual mass from combustion and the original mass of the sample.

Figure 3.9: The TGA equipment

3.5 General Gasification Setup

The gasification experiment was conducted in an open-air environment and the gasification setup is as shown in Figure 3.10. This type of mild steel gasifier has a thermal output of 50 kW, internal diameter of 400 mm, height of one meter, air inlet diameter of one inch and flue gas outlet of 1-½ inch. A cyclone unit was attached in order to have a cleaner syngas emission. The air was supplied using a dual arrangement blower modeled Ken 4210, Shanghai Ken Tools Vortex Blower and the air was controlled using conventional ball valves. Syngas combustibility was tested using a handheld butane torch at the top of the funnel.

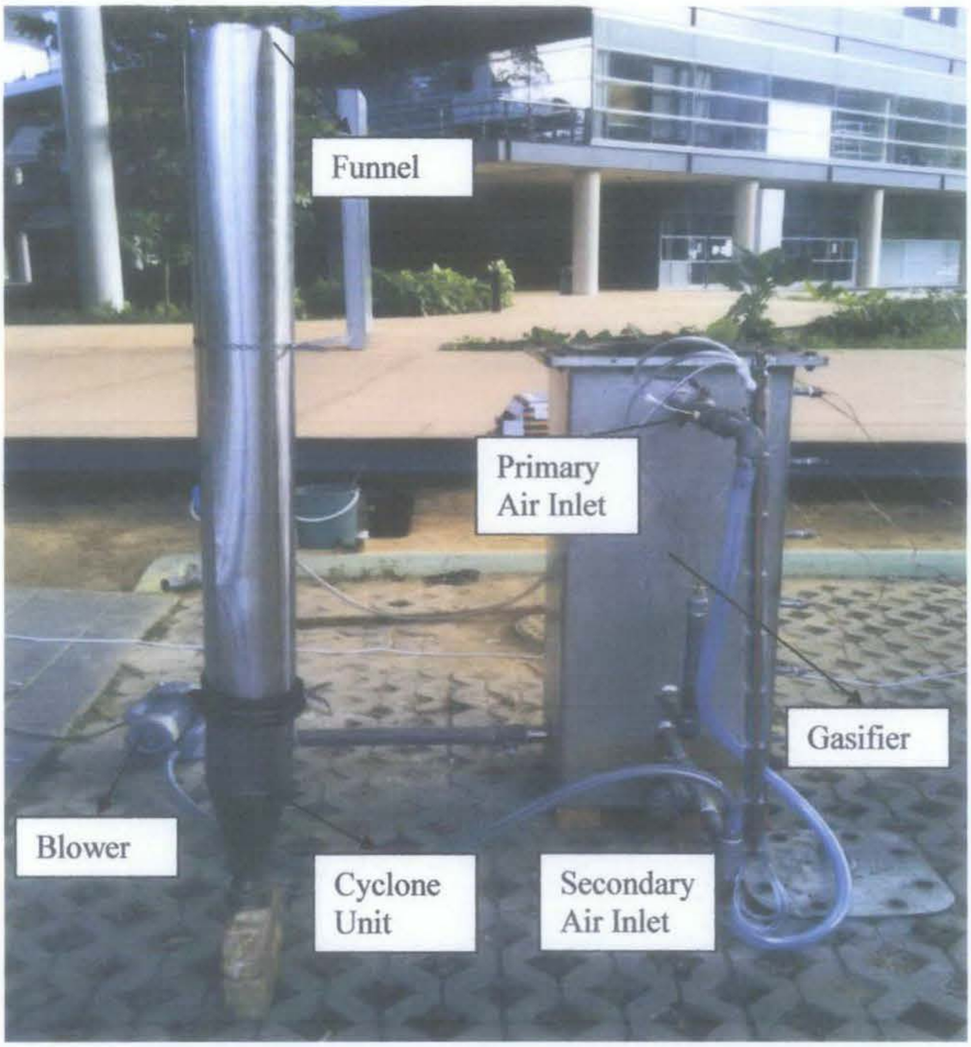


Figure 3.10: Downdraft gasification experiment setup 1

Five to six Type-N thermocouples were connected into the gasification bed in order to record the temperature of each reactor zone during gasification. A Type-K portable thermocouple was connected to the flare tip and outlet to determine the temperature as well. All type-N thermocouples were connected to a desktop computer via a USB thermocouple logger for continuous monitoring and recording purposes. A gas sampling train was connected to the exhaust pipe for gas samples extraction during gasification into gasbags. Unfortunately, only woods gasification experiment was attached with gas sampling train to collect gas due to the malfunction of the Gas Chromatography (GC) analyzer. Others were being simulated in the Engineering Equation Solver (EES).

Three-way water tube manometers were also attached to air inlet pipe, reactor body and exhaust pipe. These manometer attachments were meant for pressure monitoring and calculation of air intake.

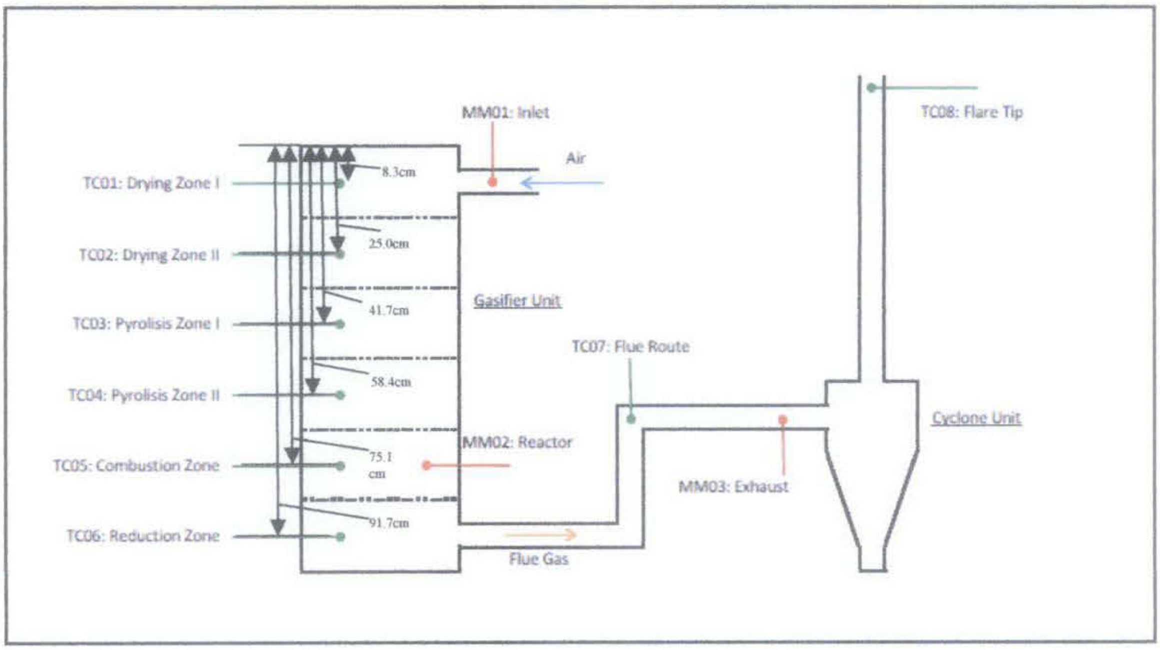


Figure 3.11: Schematic of the downdraft gasifier setup and location of measuring points (Moni, 2010)

Figure 3.11 shows schematic of the downdraft gasifier setup and the location of measuring instrument. TC01-TC08 represent the temperature measurement points using N-type thermocouple; MM01-MM03 represents the pressure gauges of the manometer.

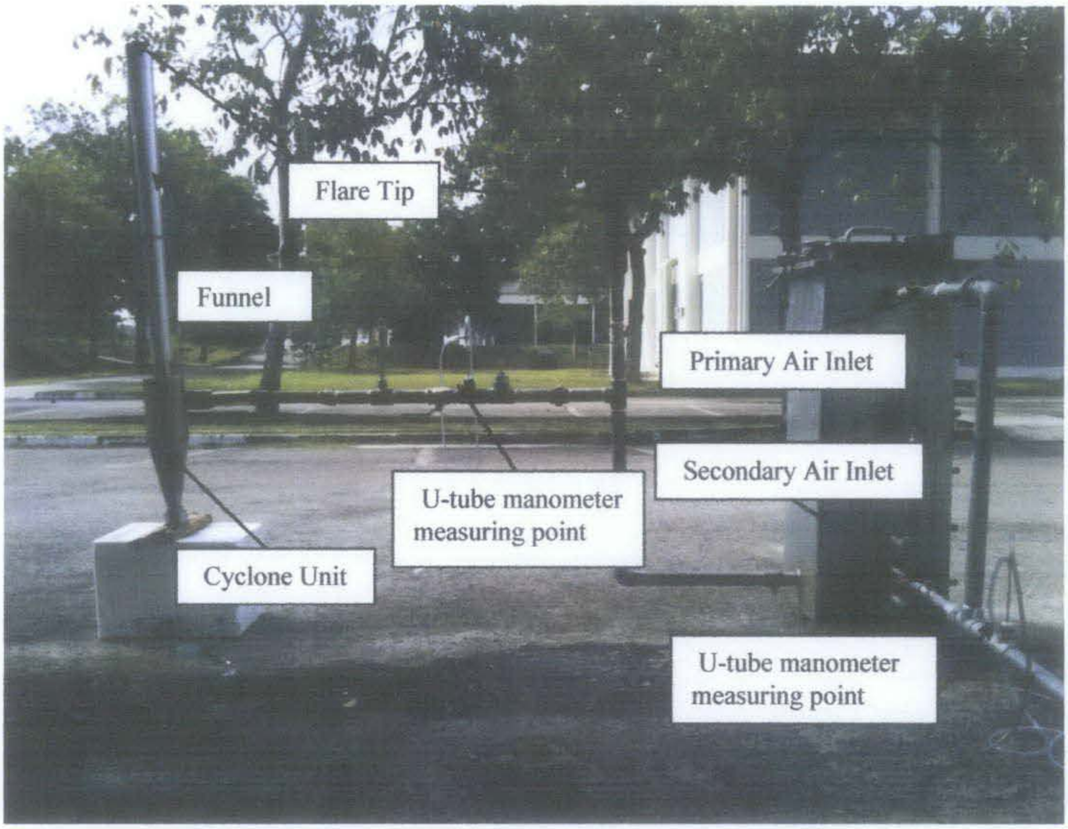


Figure 3.12: Gasification experiment setup 2

The gasification setup shown in Figure 3.10 was considered to be the main setup. Another setup which is shown in Figure 3.12 was also used in this research with slight modification. The second setup has two flare points, before and after the cleaning process from the cyclone unit. The three points manometer will be replaced by a water-based U-tube manometer. The air inlet will be the same as the previous setup.

For the first three experiments, oil palm fronds, sugarcane bagasse and woods were used in the first gasification setup. The fourth experiment, coconut husks was used in the second gasification setup. Once the gasifier was set up, gasification process follows and the results was analyzed. If there was no syngas produced, it is possible that some margin of error occurred during the pre-treatment. In that case, the pre-treatment was carried out once again before gasifying the feedstock. If the syngas was produced, vital information was recorded such as temperature of each zone in the gasifier, flame properties, combustion residue and amount of tar produce.

3.6 Gas Chromatography

Gas chromatography is a common type of chromatography used in analytic chemistry for separating and analysing compounds that can be vaporized without decomposition. Typical uses of GC include testing the purity of a particular substance, or separating and determining the different components of a mixture. In some situations, GC may help in identifying a compound. In preparative chromatography, GC can be used to prepare pure compounds from a mixture.

In gas chromatography, the mobile phase is a carrier gas, usually an inert gas such as helium or an unreactive gas such as nitrogen. The stationary phase is a microscopic layer of liquid or polymer on an inert solid support, inside a piece of glass or metal tubing called a column. The instrument used to perform gas chromatography is called a gas chromatograph.

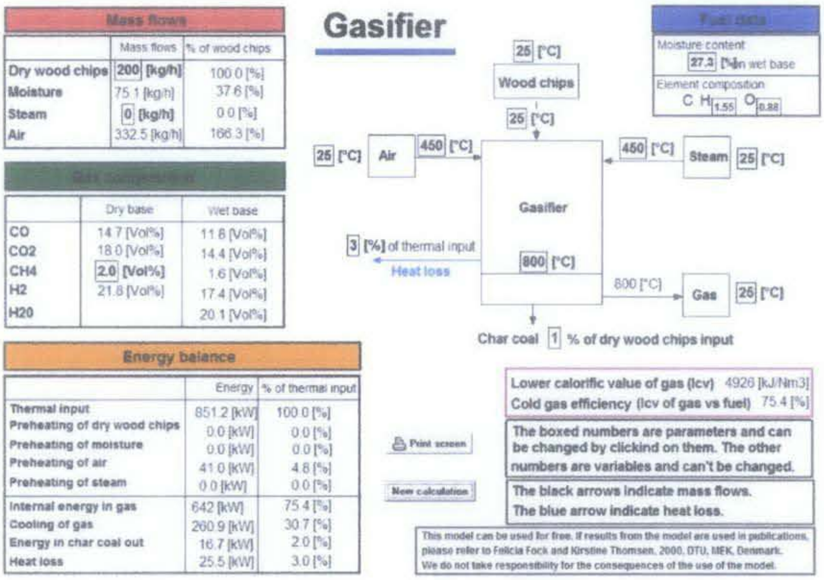
The gaseous compounds being analyzed interact with the walls of the column, which is coated with different stationary phases. This causes each compound to elute at a different time, known as the retention time of the compound. The comparison of retention times is what gives GC its analytical usefulness. After collecting the syngas from the experiments, the gas bags were sent to the GC lab for determining the syngas composition.

3.7 Engineering Equation Solver

In Technical University of Denmark, a stationary computer model of a CHP plant for thermal gasification of biomass has been built in "Engineering Equation Solver" (EES). This model can simulate many downdraft gasifiers, by adjusting the input parameters accordingly.

The fundamental equations in the model are conservation of mass and energy. In modelling the pyrolysis unit, the energy demand for this unit is calculated as the difference in the energy contents of the incoming and outgoing flows. The composition of the pyrolysis products in the outgoing flows is determined by means of experimental data.

Determination of the gas composition from the gasification chamber is based on equations for element balances and the water gas shift equation. The water gas shift equation is a temperature dependent equation for chemical equilibrium between hydrogen, carbon dioxide, carbon monoxide and water (gas phase). Figure 3.13 shows the main diagram of the EES model



Mass flows

	Mass flows	% of wood chips
Dry wood chips	200 [kg/h]	100.0 [%]
Moisture	75.1 [kg/h]	37.6 [%]
Steam	0 [kg/h]	0.0 [%]
Air	332.5 [kg/h]	166.3 [%]

Gas composition

	Dry base	Wet base
CO	14.7 [Vol%]	11.8 [Vol%]
CO2	18.0 [Vol%]	14.4 [Vol%]
CH4	2.0 [Vol%]	1.6 [Vol%]
H2	21.8 [Vol%]	17.4 [Vol%]
H20		20.1 [Vol%]

Energy balance

	Energy	% of thermal input
Thermal input	851.2 [kW]	100.0 [%]
Preheating of dry wood chips	0.0 [kW]	0.0 [%]
Preheating of moisture	0.0 [kW]	0.0 [%]
Preheating of air	41.0 [kW]	4.8 [%]
Preheating of steam	0.0 [kW]	0.0 [%]
Internal energy in gas	642 [kW]	75.4 [%]
Cooling of gas	260.9 [kW]	30.7 [%]
Energy in char coal out	16.7 [kW]	2.0 [%]
Heat loss	25.5 [kW]	3.0 [%]

Fuel data

Moisture content
27.3 [%] in wet base
Element composition
$C\,H_{1.55}\,O_{0.88}$

Lower calorific value of gas (lcv) 4926 [kJ/Nm3]
Cold gas efficiency (lcv of gas vs fuel) 75.4 [%]

The boxed numbers are parameters and can be changed by clickind on them. The other numbers are variables and can't be changed.

The black arrows indicate mass flows.
The blue arrow indicate heat loss.

This model can be used for free. If results from the model are used in publications, please refer to Felicia Fock and Kirstine Thomsen. 2000. DTU, MEK, Denmark. We do not take responsibility for the consequences of the use of the model.

Figure 3.13: Main diagram of the EES model

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Energy Analysis of the Feedstock

The energy analysis for all of the feedstock has been carried out in the IKA C-5000 bomb calorimeter and the results are shown in Table 4.1:

Table 4.1: Energy analysis of each feedstock

Energy analysis of OPF

No	Weight in g	HHV(J/g)
1	0.4561	18375
2	0.3972	17732
3	0.4237	18124
4	0.3593	17341
5	0.4781	19349
Average	**0.4229**	**18184**

Energy analysis of coconut husk

No	Weight in g	HHV(J/g)
1	0.3552	17305
2	0.4562	16285
3	0.3784	16639
4	0.4470	17229
5	0.3135	16857
Average	**0.3899**	**16863**

Energy analysis of sugarcane bagasse

No	Weight in g	HHV(J/g)
1	0.1475	19732
2	0.2331	18467
3	0.2898	18859
4	0.1975	17992
5	0.1479	19142
Average	**0.2032**	**18838**

Energy analysis of "Bakau" woods

No	Weight in g	HHV(J/g)
1	0.2925	19259
2	0.4567	21578
3	0.3895	22489
4	0.4421	23592
5	0.3957	24543
Average	**0.3953**	**22292**

From the data in Table 4.1, it can be seen that "Bakau" woods contained the highest calorific value of 22292J/g. The lowest calorific value was the sugarcane bagasse at 18838J/g. According to the India's Institute of Science, the average calorific value of typical biomass is in the range of 4-5% MJ/kg. By comparing the HHV value of each fuel with the HHV value of producer gas, it is obvious that all of them have the potential of producing syngas from gasification. This is because the HHV value of the feedstock is much higher than the HHV value of the producer gas.

The HHV value difference was calculated for sugarcane bagasse, coconut husk and "Bakau" woods with oil palm fronds.

HHV difference of sugarcane bagasse = $18838 - 18184/_{18184}$ x 100%

= 3.59%

HHV difference of coconut husk = $16863 - 18184/18184$ x 100%

= -7.26%

HHV difference of "Bakau" woods =$22292 - 18184/18184$ x 100%

= 22.59%

From the simple calculation above, it is clear that "Bakau" woods contained the largest HHV percentage difference at 22.59% while sugarcane bagasse contained the smallest HHV percentage difference at 3.59%. Early hypothesis from this calculation deduce that although "Bakau" woods contained the highest HHV value, it is the least comparable with oil palm frond in terms of energy content.

4.2 Ultimate Analysis of the Feedstock

The ultimate analysis for all of the feedstock has been carried out in the Leco CHNS-932 analyzer and the results are shown in Table 4.2.

Histogram graph as shown in Figure 4.1 was also constructed using the data from Table 4.2. From figure 4.1, all of the fuels were shown to have significant amount of carbon content of approximately 46.4 wt%. Calculating the composition by difference, it was found that the oxygen content constituted more than 49.83 wt% of each fuel. For hydrogen, the average amount is up to 6.98 wt%. As for the sulphur and nitrogen, the average is 0.24 wt% and 0.05 wt%.

Table 4.2: Ultimate analysis of feedstock

OPF MC=21%

No	Weight in mg	C%	H%	N%	S%
1	1.761	49.73	7.284	0.293	-0.047
2	1.868	46.68	7.035	0.273	-0.014
3	1.705	47.04	8.118	0.314	0.021
4	1.769	48.48	8.869	0.429	0.066
5	1.966	50.36	9.383	0.332	0.079
6	1.687	48.26	9.206	0.393	0.037
Average	**1.793**	**48.43**	**8.316**	**0.339**	**0.024**

Woods MC=11%

No	Weight in mg	C%	H%	N%	S%
1	1.567	50.74	8.331	0.022	0.067
2	1.872	52.37	7.451	0.034	0.084
3	1.934	54.76	7.831	0.039	0.091
4	1.768	51.23	8.267	0.029	0.061
5	1.789	49.74	8.987	0.041	0.059
6	1.923	53.67	7.693	0.036	0.074
Average	**1.809**	**52.09**	**8.093**	**0.034**	**0.073**

Bagasse MC=23%

No	Weight in mg	C%	H%	N%	S%
1	1.873	44.88	4.678	0.130	0.004
2	1.679	46.76	5.438	0.244	-0.038
3	1.779	47.57	5.414	0.097	0.028
4	1.937	43.29	5.837	0.312	0.049
5	1.826	48.82	6.143	0.178	-0.046
6	1.883	43.38	5.037	0.221	0.075
Average	**1.830**	**45.78**	**5.425**	**0.197**	**0.072**

Coconut MC=15%

No	Weight in mg	C%	H%	N%	S%
1	1.589	40.48	5.880	0.210	0.060
2	1.782	41.89	5.993	0.431	0.082
3	1.698	39.87	5.762	0.375	0.054
4	1.874	40.74	6.472	0.567	0.063
5	1.934	37.57	5.321	0.449	0.049
6	1.667	36.39	6.979	0.362	0.077
Average	**1.757**	**39.49**	**6.068**	**0.399**	**0.064**

Note: Moisture content was measured using HR73 halogen analyzer

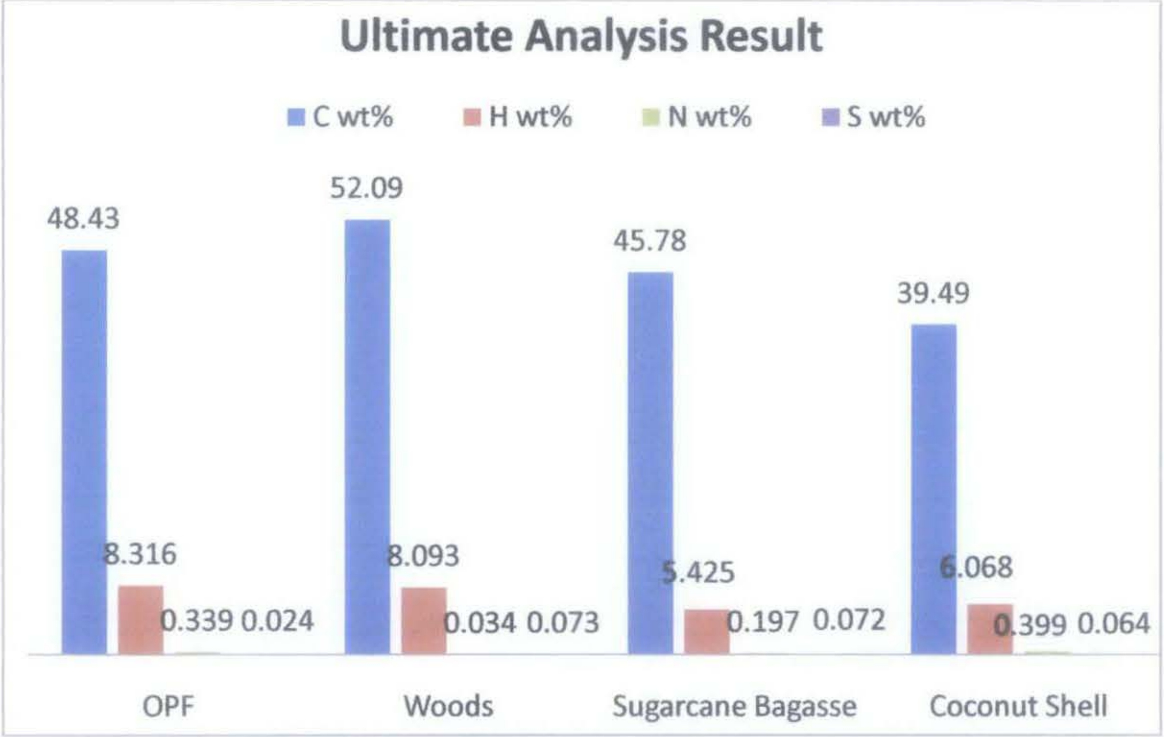


Figure 4.1: Ultimate analysis of feedstock

4.3 Proximate Analysis of the Feedstock

The proximate analysis for all of the feedstock has been carried out in the Perkins Elmer Pyris TGA-7 and the results are shown in Table 4.3:

In general, the moisture content of each feedstock was below 30% and the need to evaporate the additional moisture content was not necessary. Ash content for each feedstock was found to be below 12% which indicated the occurrence of slagging is highly unlikely. Combination of fixed carbon and volatile matter constituted almost 80% of the total component which is in agreement with literature.

Table 4.3: Proximate analysis of the feedstock

OPF

Element	Moisture Content	Volatile Matter	Fixed Carbon	Ash Content
1	5.00%	53.42%	34.48%	7.10%
2	6.00%	51.76%	36.23%	6.01%
3	5.00%	56.97%	30.28%	7.75%
Average	**5.33%**	**54.05%**	**33.64%**	**6.96%**

Sugarcane Bagasse

Element	Moisture Content	Volatile Matter	Fixed Carbon	Ash Content
1	20.00%	65.24%	12.11%	2.65%
2	21.00%	67.39%	9.06%	2.55%
3	21.00%	63.26%	12.88%	2.86%
Average	**20.67%**	**65.30%**	**11.35%**	**2.69%**

Woods

Element	Moisture Content	Volatile Matter	Fixed Carbon	Ash Content
1	11.00%	41.89%	38.74%	8.37%
2	11.00%	41.51%	39.86%	7.63%
3	11.00%	38.24%	42.77%	7.99%
Average	**11.00%**	**40.55%**	**40.46%**	**8.00%**

Coconut Husks

Element	Moisture Content	Volatile Matter	Fixed Carbon	Ash Content
1	6.00%	48.17%	41.17%	4.66%
2	7.00%	49.53%	38.99%	4.48%
3	7.00%	46.69%	42.04%	4.27%
Average	**6.67%**	**48.13%**	**40.73%**	**4.47%**

4.4 OPF Downdraft Gasification Experiment

The first experiment was done on 1st September 2010. The duration of the experiment was 120 minutes. The biomass used for the experiment was 16 kg of oil palm fronds. The size of the OPF was reduced to 1~2 inch in diameter and length and the moisture content was found to be 27.30% (wet basis). Figure 4.2 shows the temperature profile of each zone in OPF gasification.

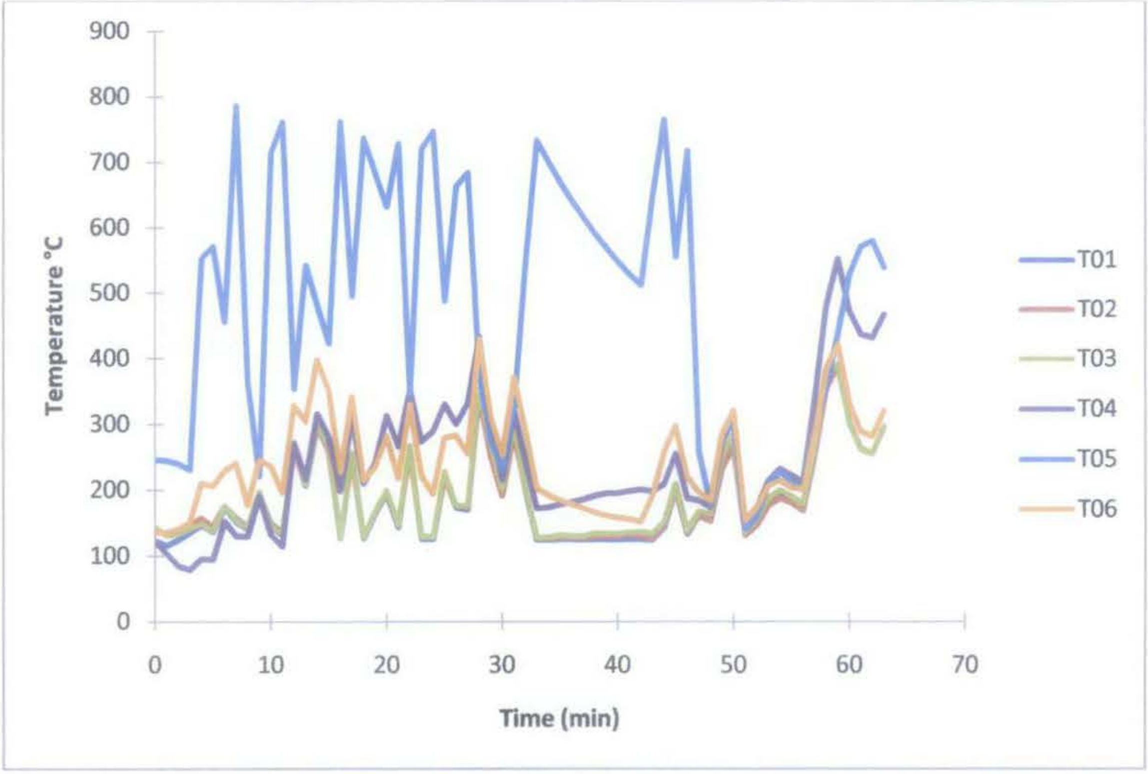


Figure 4.2: Temperature profile of each zone in OPF gasification

Figure 4.3: Flare produced from OPF gasification

The experiment was a success whereby flare can be produced from the syngas as shown in Figure 4.3. The temperature pattern of the combustion zone was close to the theoretical value of 1000°C in order to achieve gasification (Rajvanshi, 1986). The maximum flue gas temperature recorded was 313°C using mobile thermocouple. Most flares were able to be lit up and maintained for 2~3 minutes. Yellowish and orange flares were produced. Almost no liquefied tar/condensates were collected in the collection pot, mainly due to the high exhaust temperature of more than 150°C. The optimum pressure of the manometer is (16, 8, 10) inch of water. Dynamic pressure, air speed and volumetric flow rate was calculated using the following formulas:

$$\Delta P = \rho . g . h$$

where ρ is the manometer fluid density (distilled water @ 25°C), 997.044kg/m^3, h is the height of fluid column in meter and g is the gravitational acceleration, 9.81 m/s^2. The calculated value of dynamic pressure, ΔP is equal to 1491Pa.

$$\Delta P = \rho . v^2/2$$

where ρ is the air density, 1.184kg/m^3, v is the air speed, m/s. The calculated value of air speed, v is equal to 50.19m/s.

$$Q = v.A$$

where A is the pipe cross section area, 5.067×10^-4 m^2 (diameter of pipe is 1 inch), v is the air speed, m/s. The calculated value of volumetric flow rate, Q is equal to 0.025m^3/s.

4.5 Sugarcane Bagasse Downdraft Gasification Experiment

The second experiment was conducted on 1st September 2010. The duration of the experiment was 120 minutes. The biomass used for the experiment was 10 kg of sugarcane bagasse. The size of the sugarcane bagasse was not altered and the moisture content was found to be 23% (wet basis). Figure 4.4 shows the temperature of each zone for sugarcane bagasse gasification and Figure 4.5 shows the flare produced from sugarcane bagasse gasification.

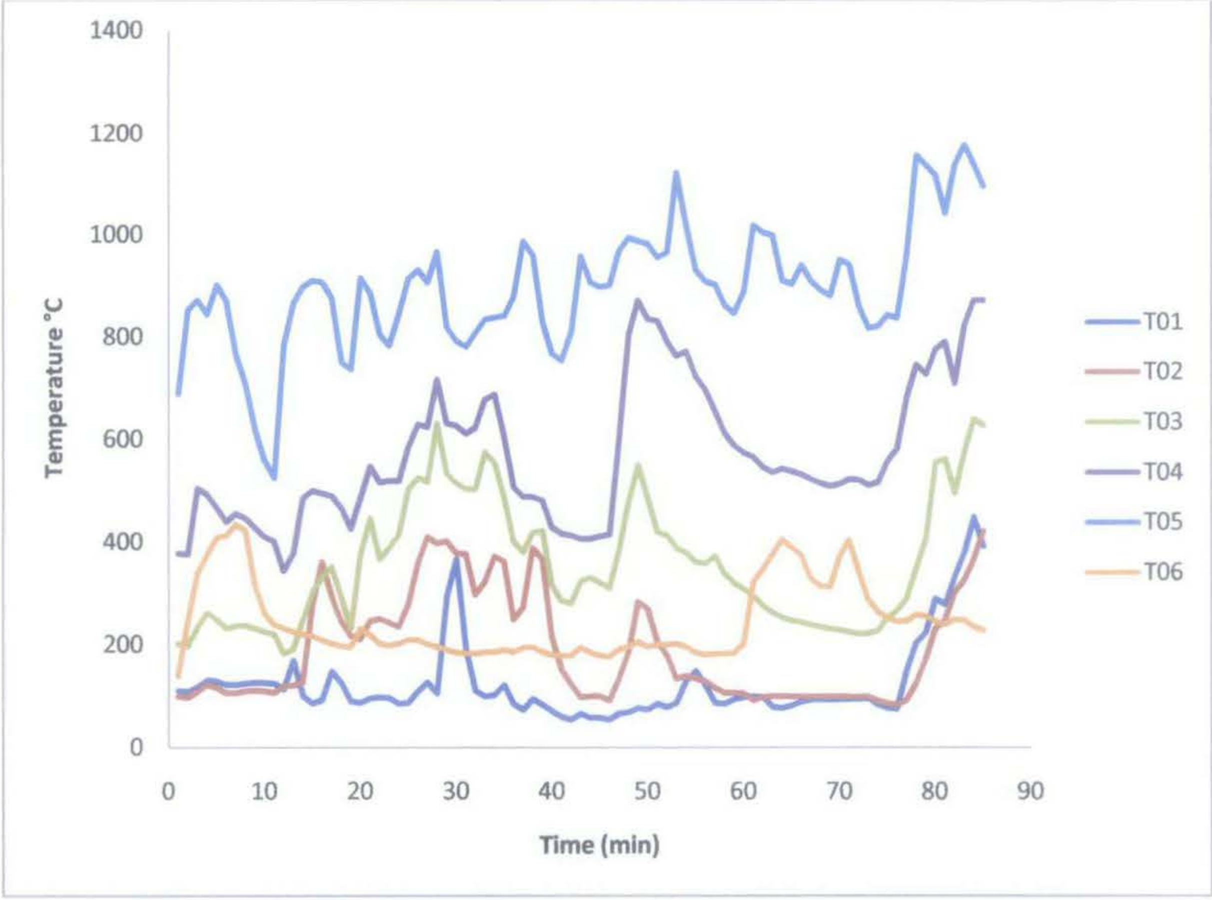


Figure 4.4: The temperature of each zone for sugarcane bagasse gasification

Figure 4.5: Flare produced from sugarcane bagasse gasification

Shown in Figure 4.6 is the temperature profile for the different gasification zones over a period of 12 minutes when flare is obtained.

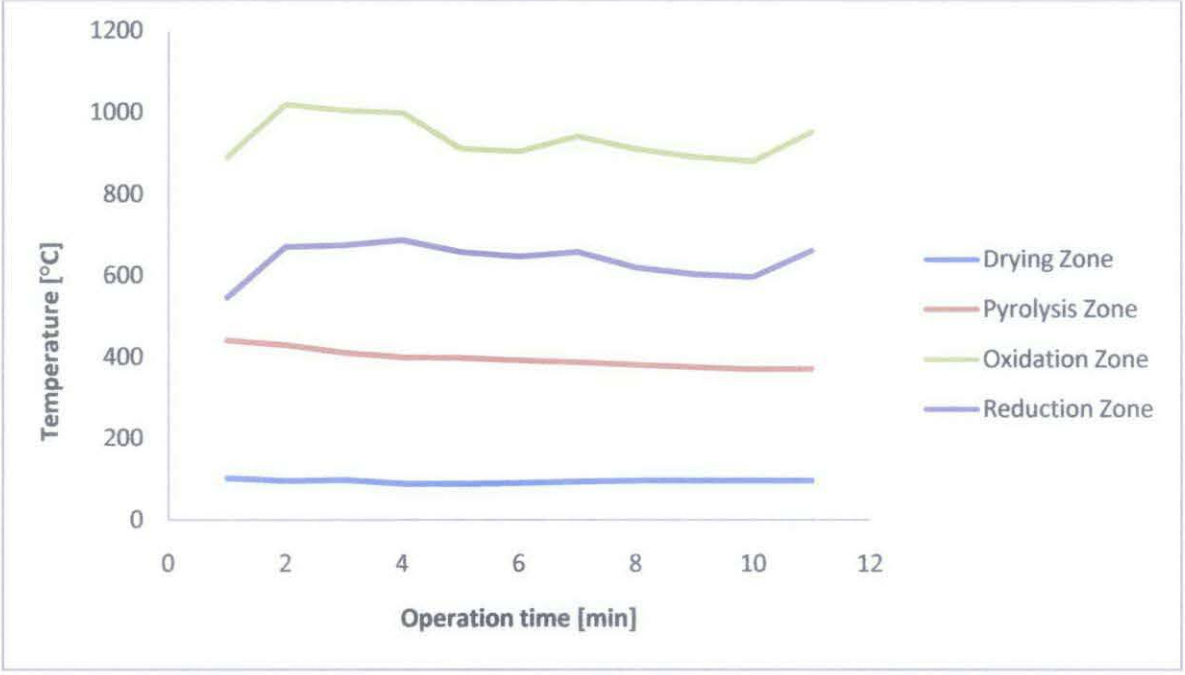


Figure 4.6: Temperature profile when flare was produced

Figure 4.7-4.9 shows the temperature distribution along the length of gasifier at different operation points when flare was obtained and it shows that the temperature of the different gasification zones and the general temperature distribution along the gasifier bed is in agreement with literature.

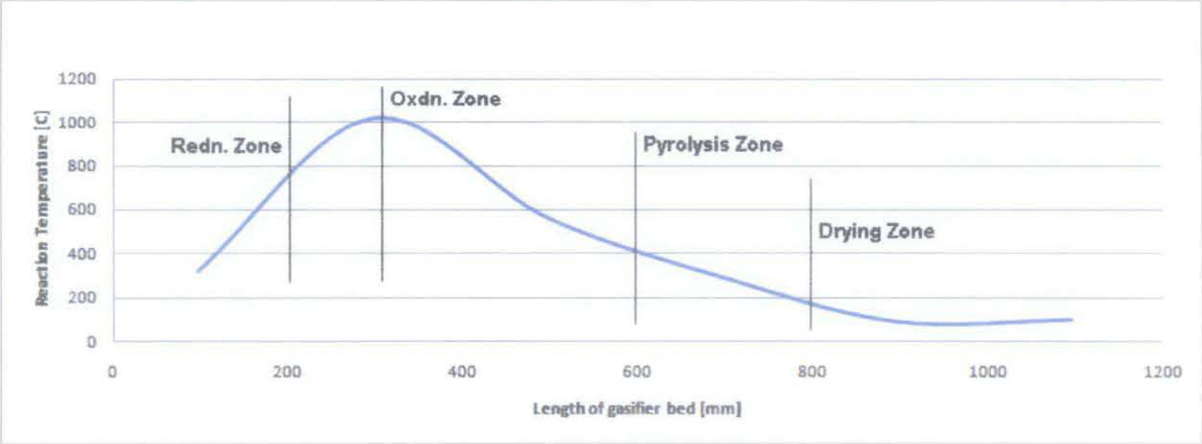


Figure 4.7: Temperature distribution along gasifier bed at flaring

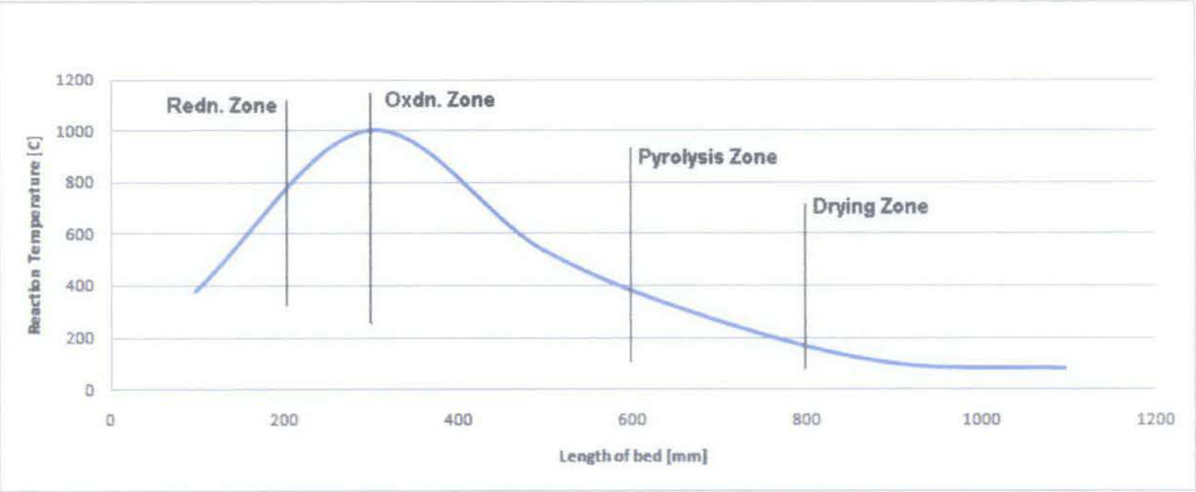


Figure 4.8: Temperature distribution along gasifier bed at flaring (2)

Figure 4.9: Temperature distribution along gasifier bed at flaring (3)

Initially, temperature of combustion zone was quite low at less than 400°C and no syngas could be detected. This may be the result of uneven distribution of feedstock inside the gasifier or the moisture content of sugarcane bagasse was quite high. Besides that, there seems to be a bridging problem whereby the sugarcane bagasse was found stuck at the drying zone 2 and pyrolysis zone 1. This is mainly due to the broom-like extremities and fibrous physical properties of sugarcane bagasse. Syngas was produced after clearing the bridging problem by opening the hopper and stirring the feedstock.

Although the gasification experiment of sugarcane bagasse produced a much bigger, stable flare than OPF, the tar formation was quite severe. Besides that, the frequency of bridging problem was high; the hopper had to be opened several times to stir the feedstock. The temperature pattern of the combustion zone exceeds the theoretical value of 1000°C in order to achieve gasification (Rajvanshi, 1986). The maximum flare gas temperature recorded was 480°C using mobile thermocouple. Flares were able to be lit up and maintained for 3~4 minutes. Yellowish and orange flares were produced. The optimum pressure of the manometer was (16, 8, 10) inch of water. Since the pressure of the manometer was similar to the OPF gasification experiment, hence the speed of air, v is equal to 50.19m/s and volumetric flow rate, Q is equal to 0.025 m^3/s.

4.6 Woods Downdraft Gasification Experiment

The third experiment was conducted on 20th October 2010. The duration of the experiment was 120 minutes. The biomass used for the experiment was 10 kg of Rhizophocea Woods. The size of the Rhizophocea woods was reduced to 1~2 inch in diameter and length and the moisture content was found to be 11% (wet basis) using HR73 halogen analyzer. Shown in Figure 4.10 is the flare produced from woods gasification.

Figure 4.10 Flare produced from woods gasification

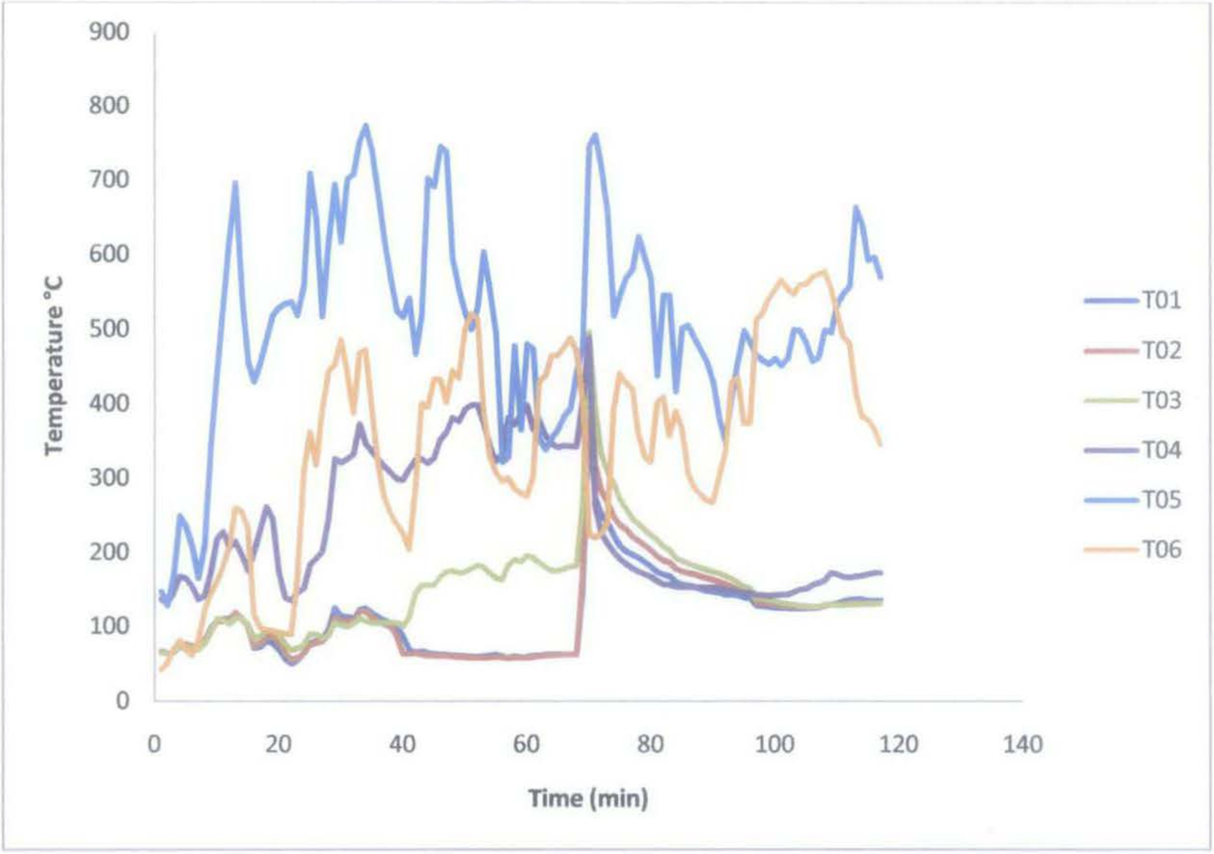


Figure 4.11 Temperature profile of each zone in woods gasification

Figure 4.11 shows the temperature profile of each zone in woods gasification. The setup for Rhizophocea woods was slightly different whereby a gas sampling train was attached to collect the syngas for composition analysis. Overall, the gasification was a success as flare can be lit up and maintained for 4~5 minutes. There was no bridging problem and no tar formation could be detected. However, the average combustion zone was at 600°C which is slightly lower than the theoretical value. This indicates the energy required to achieve gasification is lower possibly due to the low moisture content.

The maximum flare gas temperature recorded was 407°C using mobile thermocouple. Yellowish and orange flares were produced. No traces of blue flame could be seen indicating that the presence of hydrogen is less. The optimum pressure of the manometer was (25, 12, 14) inch of water. The speed of air, v is equal to 67.95m/s and volumetric flow rate, Q is equal to $0.034m^3/s$.

The syngas was collected using a gas bag and GC analysis was done in a bio-hydrogen lab. The result shown in Table 4.4 indicates that hydrogen constitutes the highest percentage in syngas at 51.69% while methane constitutes the lowest percentage at 2.46%.

Table 4.4: Gas chromatography result of Rhizophoraceae woods syngas

Chemical Composition	GC Analysis Result	Overall Percentage of The Syngas	Relative Percentage of The Syngas
CO_2	13,715.10 ppm	(1.3715%)	(31.99%)
CH_4	1,052.60 ppm	(0.1053%)	(2.46%)
CO	5,944.12 ppm	(0.5944%)	(13.87%)
H_2	22,158.00 ppm	(2.2158%)	(51.69%)

4.7 Coconut Shell and Husks Downdraft Gasification Experiment

The fourth experiment was conducted on 22nd June 2011. The duration of the experiment was 60 minutes. The biomass used for the experiment was 4~5 kg of coconut shell and husks. The size of the coconut shell and husks were not altered and the moisture content was found to be 13% (wet basis) using HR73 halogen analyzer. Figure 4.12 shows the flare produced from coconut shell and husks gasification.

Figure 4.12 Flare produced from coconut shell and husks gasification

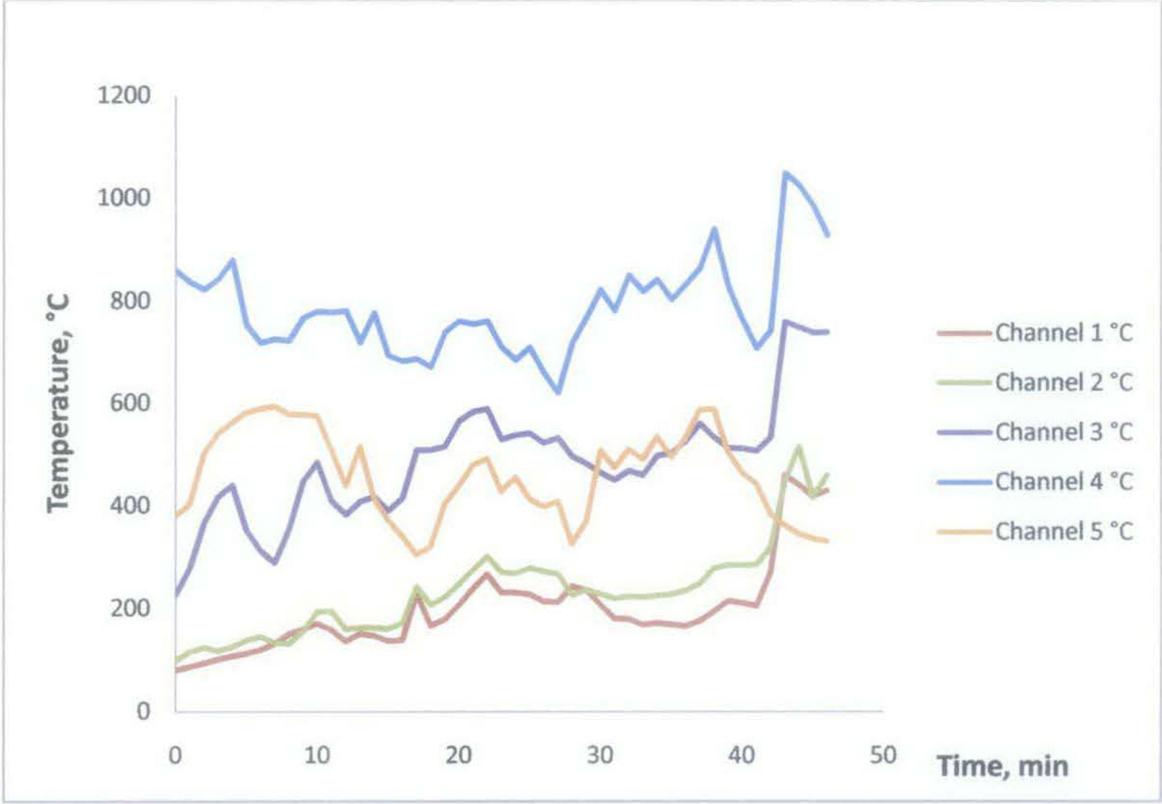


Figure 4.13 Temperature profile of coconut shell and husks gasification

The temperature profile of coconut shell and husks gasification is shown in Figure 4.13. Overall, the gasification did produce syngas and the flare could be maintained for about 4-5 minutes. However, through observation and in comparison with previous experiments, the number of times that the output gas could be flared decreases. Tar could be found around the gasifier and during experiment, the flow rate of air in the pipe was not smooth. This is probably due to clogging or blockage in the pipe itself.

The air inlet pressure is 1-1.5 mm; the air outlet pressure is 2-3.5 mm. The reason for the variation of value is because manipulation of the flow rate of air using the valve is necessary to achieve better flare of syngas. The average value of air inlet pressure is 1.25 mm and 2.75 mm for air outlet pressure.

Using the following formula to calculate flow velocity,

$$V = \sqrt{\frac{2 \times \rho_{Water} \times g \times \Delta h}{\rho_{Air}}}$$

where V is equal to flow velocity inside pipe [m/s], ρ_{Air} is the density of air, [at S.T.P 1.2041 kg/m^3], ρ_{Water} is the density of water, [1000 kg/m^3], g is gravitational acceleration, [9.81 m/s^2] and Δh is the water differential pressure [m]. For 1-½ inch dimension of air inlet pipe, the internal diameter of the pipe is taken to be 37.5 mm and the area, A is equal to 1.1045× 10^-3 m^2. Thus the inlet velocity, v is equal to 4.513 m/s, the inlet volumetric flow rate, Q is equal to 4.985 m^3/s. The outlet flow velocity, v is equal to 6.694 m/s and the outlet volumetric flow rate, Q is equal to 7.394 m^{3}3/s. The maximum flare temperature recorded was quite low at 202.3 °C, and the outlet temperature was 165.7 °C.

4.8 Engineering Equation Solver (EES) Result

Table 4.5 lists down the simulation results from EES for each biomass and the GC analysis of woods. Technically, syngas contains two major elements, carbon monoxide plus hydrogen. From the results shown in Table 4.5, it is noticeable that in all of the biomass, the two major elements dominated more than 50% of the total syngas composition. This can be explained by the downdraft arrangement of the gasifier because throughout the fixed-bed, higher average temperatures lead to larger efficiencies and carbon conversion (Marcio, 2010). The percentage of methane composition for all the biomass was rather small, averaging at 3.925%. This is probably due to the poor reaction of devolatilization due to high temperatures in the downdraft gasifier.

Table 4.5: Results from Engineering Equation Solver (EES)

Biomass	CO%	H_2%	CO_2%	CH_4%
OPF (EES)	23.69	37.71	35.03	3.57
Sugarcane Bagasse (EES)	24.77	28.25	44.89	2.09
Woods (GC)	13.87	51.69	31.98	2.46
Coconut Husks (EES)	22.94	32.74	36.74	7.58

4.9 Overall Summary of Gasification Result

Table 4.6 shows the overall summary of gasification result for all biomasses. Although each biomass was able to produce syngas, not all of the gasification experiments run smoothly. In short, only OPF and Rhiziphocea woods were able to produce syngas with no tar formation, bridging problem and slagging.

Table 4.6: Overall summary of gasification result

Biomass Used	Size	Moisture Content	Max Flue Gas Temp	Flare Produced	Observation
16 kg of OPF	1~2 inch	27.30%	313°C		Orange flare was produced and maintained for 2~3 minutes. No liquefied tar produced, due to high exhaust temperature. The temperature pattern of combustion zone is in agreement with literature.
10 kg of Sugarcane Bagasse	Fibrous	23.00%	480°C		Initially, temperature of combustion zone is below 400°C, no syngas detected initially due to bridging problem. Yellowish, orange flares were produced after clearing of bridging problem. Tar formation was quite severe around the gasifier reactor.
10 kg of Rhizophocea Woods	1~2 inch	11.00%	407°C		Stable orange flares were produced and maintained for 4~5 minutes. No bridging problem and tar formation could be detected. Resulting syngas from GC indicates carbon monoxide content at 13.87% and hydrogen content at 51.69%
5 kg of Coconut Shell and Husks	Fibrous	13.00%	165°C		A trace of bluish flare indicates the high presence of hydrogen content. Severe tar formation around the gasifier reactor. Pipe blockage due to slagging of ash.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The most promising replacement for oil palm fronds on the designated downdraft gasifier is evident from the results obtained from the present research. "Bakau" woods are able to produce stable syngas with no gasification problem and minimum tar formation. As for the sugarcane bagasse, bridging problem is evident due to its fibrous nature and broom-like extremities whereas in coconut shell and husks, blockage in piping and severe tar formation proves that they are less compatible with oil palm fronds to be gasified in the same downdraft gasifier.

The resulting temperature profile for each feedstock is in compliance with literature. Besides that the flare produced from the gasification proves that gasification took place in each experiment. Although there were many problems for some of the feedstock as mentioned above, all the experiments did produce syngas. From the syngas analysis of each biomass, carbon monoxide and hydrogen constitutes more than 50% of the syngas composition. This can be explained by the downdraft arrangement in which the efficiency and carbon conversion are higher. The percentage of methane composition for all the biomass is 3.925% due to poor devolatilization.

In a nutshell, the objective of finding a compatible biomass to the primary biomass feedstock was achieved and from the study, the most compatible biomass for oil palm fronds was Rhizophocea woods. Coconut shell and sugarcane bagasse were not compatible with oil palm fronds.

In the future, this project can be further improved by

- Slight modification on downdraft gasfier design to prevent bridging problem. This can be done by adding a rotating screw inside the gasifier.
- Add the portable syngas analyzer attachment to the existing gasifier setup. This attachment can analyze the syngas emission in real time for a more accurate result.

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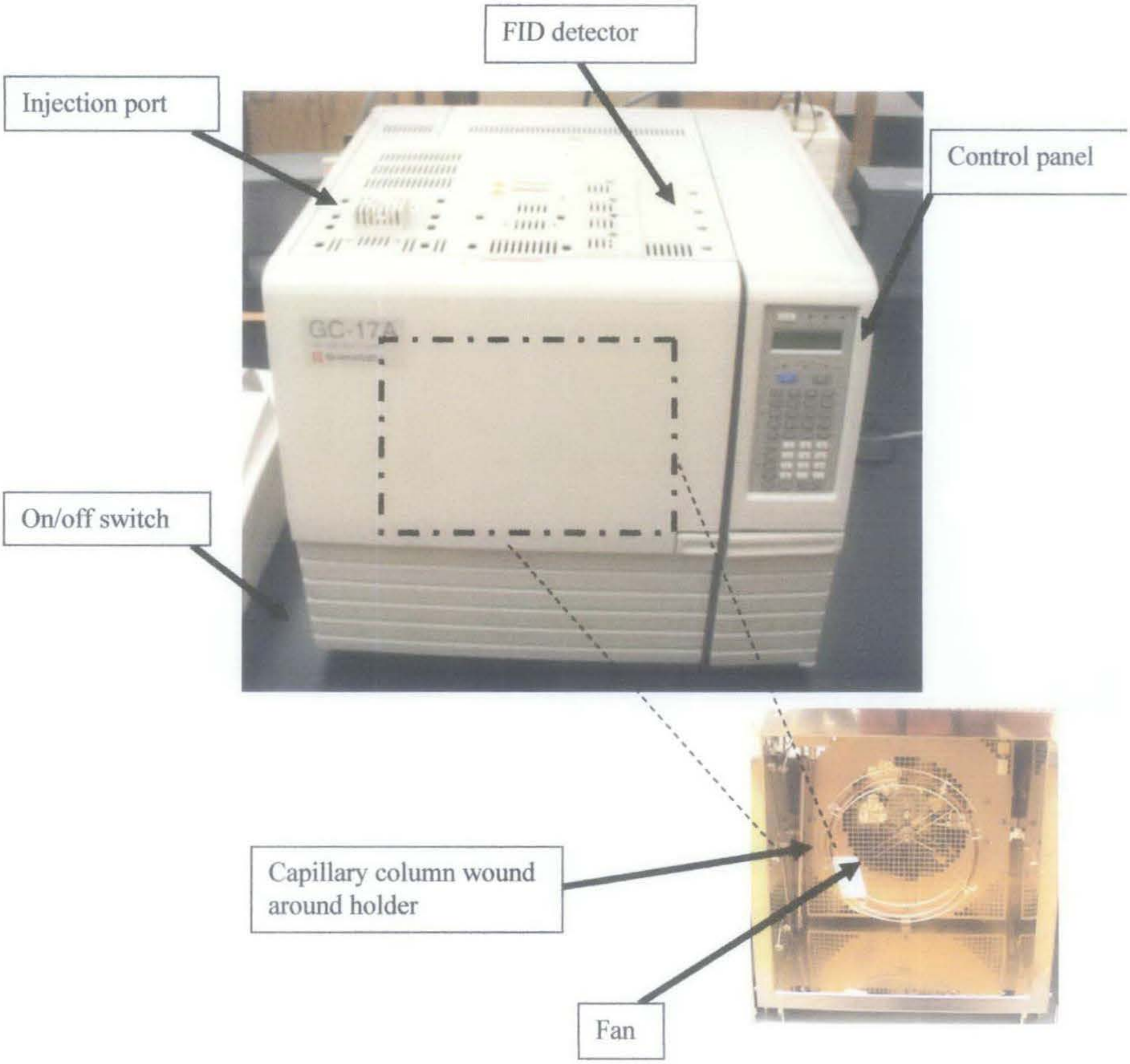
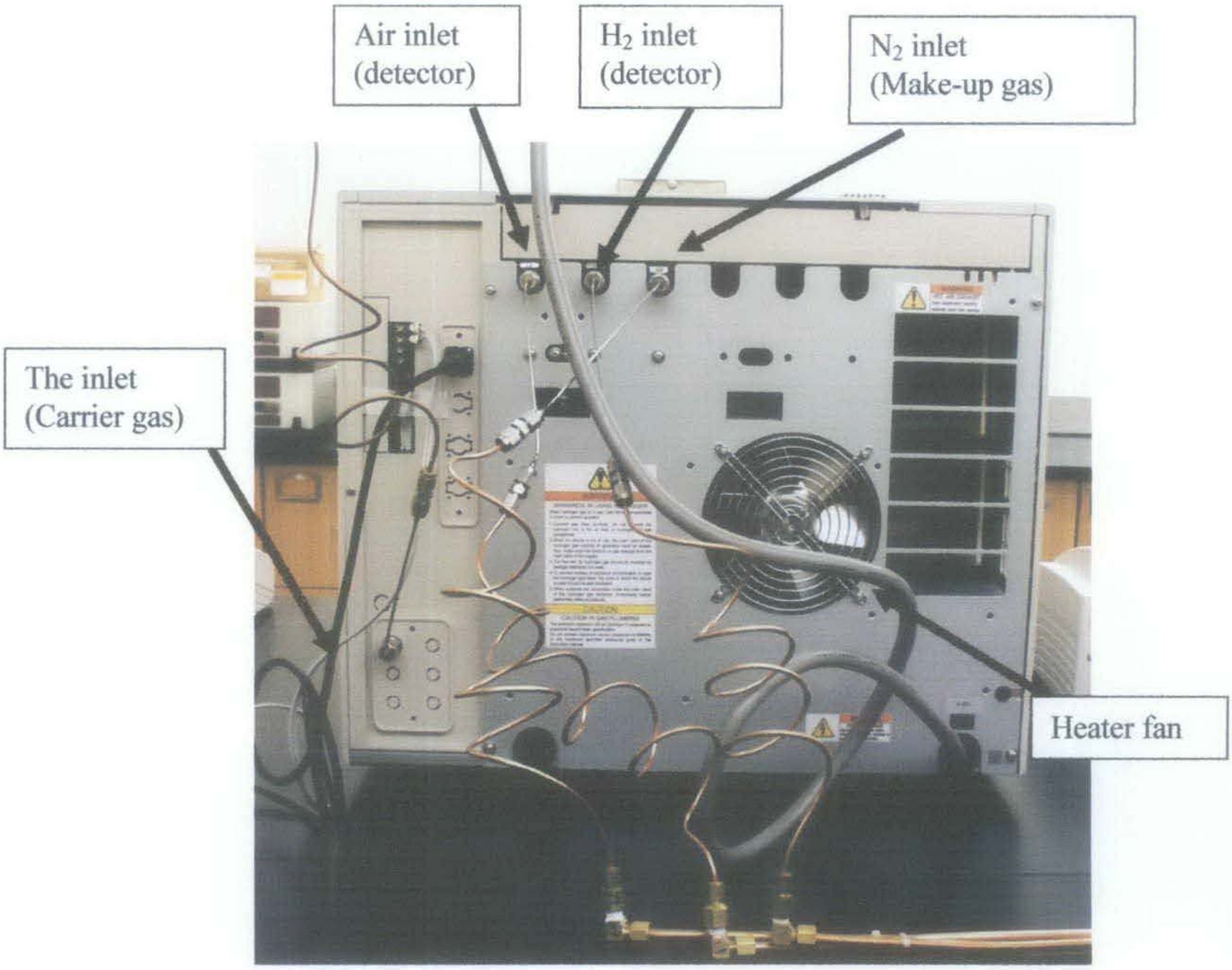
APPENDICES



Appendix A: Figure Front View of Gas Chromatograph



Appendix B: Rear View of Gas Chromatograph

```
                    2.051 g
                   ...0 %D
1:00 min         94.05 %D
2:00 min         91.13 %D
3:00 min         89.81 %D
4:00 min         89.32 %D
5:00 min         89.18 %D
6:00 min         89.08 %D
7:00 min         89.03 %D
8:00 min         88.98 %D
9:00 min         88.93 %D

otal time        10:00 mi
nd result        88.93 %D
                 1.824 g
---18.10.10---15:10---
```

Appendix C: HR73 Halogen Moisture Analyzer, Moisture Content of Sugarcane Bagasse