TORREFACTION OF WOOD PELLETS USING HEAT FROM THE PRODUCER GAS

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TORREFACTION OF WOOD PELLETS USING HEAT FROM THE PRODUCER GAS

by

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List of Abbreviations

CO	Carbon Monoxide
CO_2	Carbon Dioxide
ER	Equivalence Ratio
GC	Gas Chromatography
H_2	Hydrogen
H_2O	Water or steam
He	Helium
HHV	Higher Heating Value
HHV_B	Higher Heating Value of biomass (MJ kg^{-1})
HHV_{TB}	Higher Heating Value of torrefied biomass (MJ kg^{-1})
LHV	Lower Heating Value
LHV_B	Lower Heating Value of the biomass fuel (MJ kg^{-1})
LHV_{PG}	Lower Heating Value of the producer gas (MJ Nm^{-3})
LPM	Litre per minute (L min^{-1})
MTOE	Million Tonnes of Oil Equivalent
N_2	Nitrogen
PAH	Polycyclic Aromatic Hydrocarbon

TCD	Thermal Conductivity Detector
TGA	Thermogravimetric Analyzer

List of Symbols

C_E	Energy balance closure
Cm	Mass balance closure
E_i	Energy input (MJ h^{-1})
E_O	Energy output (MJ h^{-1})
$\dot{m}_b$	Mass flow rate of the biomass fuel (kg h^{-1})
M_i	Mass input
M_o	Mass output
MW_{PG}	Molecular Weight of producer gas (kg $kmol^{-1}$)
Q	Flow rate of air (L min^{-1})
M_{air}	Mass flow rate of air (kg h^{-1})
$M_{MC(AIR)}$	Moisture content in air (kg h^{-1})
V_{air}	Volumetric flow rate of dry air (m^3 h^{-1})
$V\mathrm{pg}$	Volumetric flow rate of the clean dry producer gas (m^3 h^{-1})
η_{cg}	Cold gas efficiency

TOREFAKSI BAGI PELET KAYU MENGGUNAKAN HABA DARI GAS PENGELUAR

ABSTRAK

Penggasan adalah proses penukaran termo-kimia yang telah terbukti menjadi sumber yang paling boleh dipercayai untuk teknologi penukaran tenaga bagi bahan api biojisim. Berkenaan dengan kekurangan bahan api fosil, penggunaan untuk bahan api biojisim meningkat dengan hebat sebagai salah satu sumber utama tenaga yang boleh diperbaharui. Penggasan biojisim adalah satu proses untuk menukar bahan bakar pepejal kepada gas mudah terbakar biasanya 3-5 MJ m^{-3} dengan suhu keluar yang boleh mencapai suhu melebihi 300^{o}C. Tujuan kajian ini adalah untuk memanafaatkan haba daripada gas pengegasan untuk proses torefaksi. Torefaksi adalah proses termo-kimia biojisim dalam julat suhu yang kecil daripada 200 ke 300^{o}C. Kajian ini melibatkan penyelidikan dengan membezakan kadar aliran udara yang masuk ke reaktor penggasan dan kesan suhu kepada reaktor torefaksi. Kualiti produk torefaksi dianalisis untuk kandungan kelembapan, kandungan volatile, kandungan karbon tetap dan kadar abu dengan nilai pemanasan sebagai kriteria utama analisis. Pelet biojisim dengan nilai pemanasan 17 MJ kg^{-1} digunakan sebagai bahan bakar untuk proses pengegasan dan bahan kajian untuk reaktor torefaksi. Profil suhu di dalam reaktor torefaksi dicatat mengikut berbezaan kadar aliran dari 150, 200, 250 dan 300 L min^{-1}. Suhu purata yang dicatatkan gas pengeluar adalah kira-kira 300-400^{o}C bagi reaktor penggasan. Nilai pemanasan rendah (LHV) gas pengeluar akan meningkat dengan peningkatan kadar aliran masuk udara. Suhu di dalam reaktor torefaksi juga meningkat dengan kadar kenaikan aliran masuk udara.

Nilai pemanasan yang lebih tinggi dari pelet biojisim yang diperolehi dari proses torefaksi adalah di dalam lingkungan 19-24 MJ kg^{-1} dengan peningkatan sebanyak 10 hingga 40%. Didapati bahawa kadar aliran masuk udara pada 200 L min^{-1} menyebabkan suhu optimum untuk proses torefaksi pada kira-kira 300^{o}C. Pada aliran ini kesan masa dalam reaktor dan ketinggian biojisim dalam reaktor, kepada kualiti produk telah dianalisis. Berdasarkan keputusan yang diperolehi didapati bahawa peningkatan masa dalam reaktor meningkatkan kualiti produk yang terhasil. Hasil yang diperoleh dari proses ini, nilai LHV gas pengeluar menunjukkan peningkatan sebanyak 7%.

TORREFACTION OF WOOD PELLETS USING HEAT FROM THE PRODUCER GAS

ABSTRACT

Gasification is a thermo-chemical conversion process that has been proven to be the most reliable source for energy conversion technology meant for biomass fuel. With respect to depletion of fossil fuel the usage for biomass fuel is increasing tremendously as one of the key source of renewable energy. Biomass gasification is a process to convert solid fuel into combustible gases typically having heating value 3-5 MJ m^{-3} with exit temperature that can reach above 300^oC. Torrefaction is a thermo-chemical process of biomass within a narrow temperature range from 200^oC to 300^oC. The aim of this research is to utilise heat from the producer gas for torrefaction process. This study involved the investigation of varying air flow rate entering the gasifier and the effect of temperature inside the torrefaction reactor. The quality of the torrefaction product was analysed for moisture content, volatile matter, fixed carbon and ash content with heating value as the main criteria of analysis. Biomass pellets with heating value of 17 MJ kg^{-1} were used as fuel for gasification and material for torrefaction. Temperature profiles inside the torrefaction reactor were recorded for different air flow rates of 150, 200, 250 and 300 L min^{-1}. The recorded average temperature of producer gas was about $300\text{-}400^oC$ at the exit of the gasifier. Lower heating value (LHV) of the producer gas increased with increasing flow rate of air entering the gasifier. The temperature inside the torrefaction reactor also increased with respect to the flow rate of air. The higher heating value (HHV) of torrefied biomass was obtained in the range of 19-24 MJ kg^{-1} with an increase of about 10-40%. It was found that flow rate of air at 200 L min^{-1} resulted in the optimum temperature for torrefaction process at about 300^{o}C. At this flow rate the effect of the residence time and bed height on the quality of product was also analysed. Based on the results obtained it was found that increase in residence time affected the quality of the product. The result obtained for producer gas LHV showed an increase by 7%.

Chapter 1 – Introduction

1.1 Introduction

The advancement of human society has been tied to the ability to produce and harness energy. Daily activities such as heating, cooling, cooking, and entertainment require the use of energy. The importance of energy in human daily life has become the objective for any technological development to harness and to increase the efficiency of energy system in this world. The awareness of energy conservation has become critical over the concern on depletion of fossil fuels in the near future. The conventional energy resources such as coal, oil and gas are being used at a high intensity with the fear of depletion in the next century. Apart from this fear there is also an increasing awareness about environmental pollution and ways of minimising the effect (Schafer, 2005).

In Malaysia energy demand indicates rapid increase. To satisfy the increasing requirement of energy and to cut down the emission of carbon dioxide while ensuring energy security, Malaysia needs to deliver an effective and sustainable source of energy (Malaysia, 2010). Figure 1 shows the energy demand in Malaysia from 1980 to 2030. Table 1 shows data that, 97% of Malaysia energy consumption depended heavily on fossil fuel (natural gas, coal, diesel and oil) and only 0.5% of the energy came from renewable sources such as biomass excluding hydropower. If this trend is to continue, Malaysia could suffer from deficiency of energy security as Malaysia fossil fuel reserves is predicted to sustain only for another 30 to 40 years (Sabil et al., 2013).

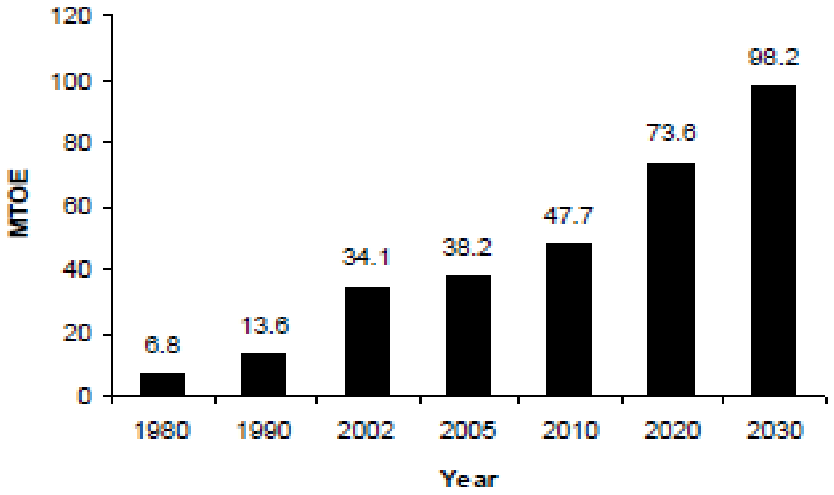

Figure 1.1: The energy demand in Malaysia (Malaysia, 2010)

The need to find reliable source of renewable energy has become critical. Renewable energy is defined as the energy that cannot deplete but replenish in a very short time. Biomass, water (hydropower), wind, solar and geothermal are common renewable that energy sources widely used in this world. Biomass energy or bioenergy accounts for the largest utilization of renewable energy.

Table 1.1: Malaysia energy mix in the year of 2012 (Tenaga, 2012)

Source	Percentage, %
Gas	46.0
Coal	18.0
Hydropower	2.5
Oil	32.8
Biomass	0.5
Others	0.2

Biomass energy has the best potential for further development and research for tapping the potential of biomass energy in creating a sustainable source of energy in the future.

1.1.1 Biomass Gasification

To produce energy from biomass, various conversion technologies such as physical, thermal, chemical and biological methods had been developed. Thermal conversion techniques include direct combustion, pyrolysis, gasification and liquefaction (Zhang et al., 2007). Biomass gasification is described as 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 of gas is called producer gas. The incomplete combustion of biomass takes place at temperature of about 800-900°C (Zainal et al., 2002).

1.1.2 Torrefaction

The problems with biomass are its characteristics. Raw biomass is characterized with high moisture content, low energy density, hygroscopic behaviour, storage difficulty and poor grindability. A pre-treatment method called ‘torrefaction’ is found to be an effective process to improve the limitations properties of raw biomass. Torrefaction is a thermo-chemical treatment process operating at a temperature ranging from 200 to 300°C (Bergman et al., 2005b). It is carried out at near atmospheric pressure in the absence of oxygen. The biomass partly decomposes during the process giving off water and various types of volatiles, which results in a slight loss of mass and chemical energy. Two different mechanisms occur during the process, firstly during drying when moisture evaporates and secondly during decomposition of biomass (Chew and Doshi, 2011).

1.2 Problem Statements

Biomass as a form of energy has a great potential to be developed for replacement of conventional energy sources. The gasification process is one of the energy conversion technologies that have the potential to be developed for use in large scale. Gasification has become popular in energy conversion process for biomass. The gas exited from the gasifier can reach temperature exceeding 300°C (Jain and Goss, 2000). Usually the gas is cooled prior to its application via internal combustion engine and gas turbine. The heat from producer gas is typically removed through the use of heat exchanger and condenser (Banapurmath et al., 2009). The heat loss to the environment is approximately 1.2 kW based on producer gas flow rate of 200 L min^{-1}.

The idea of utilizing heat from producer gas had been proposed by Prins (2005). Using circulating fluidized bed gasifier the hot gases from the gasifier is transferred to heat recovery/steam generator to produce the high pressure steam to transfer heat to torrefaction reactor. In the torrefaction reactor the heat from steam is transferred through the indirect heat transfer to obtain the required temperature for torrefaction that is below 300°C. The torrefied products obtain will directly supply to the gasifier. Hence, efficiency of the system can be improved with the ability of the system to use waste heat from producer gas.

1.3 Objectives

The present study is aimed to develop the gasification-torrefaction system and to analyse the product produced from the system. Therefore, the objectives of this research work can be summarized as follows:

1. To develop a biomass gasification-torrefaction system.

2. To determine and to characterize the torrefaction quality of wood pellets using heat from the gasification process at various flow rate, residence time and bed height.

3. To find the optimum conditions specific to the gasifier-torrefier system.

1.4 Scope

The current study will focus on the development of gasification torrefaction system through the use of conventional design to test the potential it has on the system. The study will see the ability of the gasifier to produce and utilize the producer gas for torrefaction. And then study the effect it has on the torrefied product by changing the parameters set for this study. The parameters are temperature, residence time and bed heights. These parameters are studied to find the optimum condition suitable for this system setup and to find the quality of the torrefied product. The mass and energy balances are developed to find the reliability of the system.

1.5 Thesis Outline

This thesis is divided into five chapters. Chapter 1 briefly describes the limitation of biomass energy sources, research background, and the recovery methods. The problem statement of this study is also provided. Then, the objectives and the scope of this study are highlighted. Finally, the organization of this thesis is given at the end of the chapter.

Chapter 2 consists of literature review related to this study. In this chapter, the details of biomass properties, torrefaction characteristics and gasification process are explained. Types of reactors and factors affecting torrefaction are also presented. The types of gasifiers used in the study are reviewed to give the detail specification required for the gasification process. Finally, a summary of combining torrefaction and gasification processes are presented.

Chapter 3 describes the details of experimental set-up for the gasification-torrefaction process. The materials of this study are described. The equipment for the sampling and analyses of products including gases, wood pellet and tar are presented and explained. The descriptions of process parameters are also included.

Chapter 4 present the results and discussion concerning the experimental study. The characteristics of gasifier system and temperature profile are explained in this chapter. And also the effect of the bed height, temperature and residence are discussed and described in this topic. Finally the optimum condition required to analyses the significant of torrefaction and gasification system is presented.

Chapter 5 summarizes the findings and concludes the study. Based on the results, recommendations are presented for further studies in this area.

Chapter 2 – Literature Review

2.1 Biomass

Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass (Basu et al., 2013a). Typically photosynthesis converts less than 1% of the available sunlight to the chemical energy used in building blocks of biomass. When energy stored in chemical bonds is released chemically or biologically, CO_2 and water are formed. Therefore the process is cyclic. One of the most significant differences between biomass and fossil fuels is the time required for uptake and release of CO_2. It takes millions of years to convert biomass to fossil fuels and thus they are not renewable fuels within the time-scale of mankind (Husain et al., 2003).

The value of a particular type of biomass depends on its chemical and physical properties. Biomass can be converted into three main types of product: electrical/heat energy, transport fuel, and chemical feedstock (McKendry, 2002a).

2.1.1 Biomass Components

Lignocellulosic biomass refers to three dominant polymeric structures in plants namely cellulose, hemicellulose and lignin as well as other inorganic organic chemical (McKendry, 2002a). Wood and other plant biomass is fundamentally a composite material constructed from oxygen-containing organic polymers. Figure 2.1 indicates the low-molecular and macromolecular weight substances in biomass (Sivakumar et al., 2012).

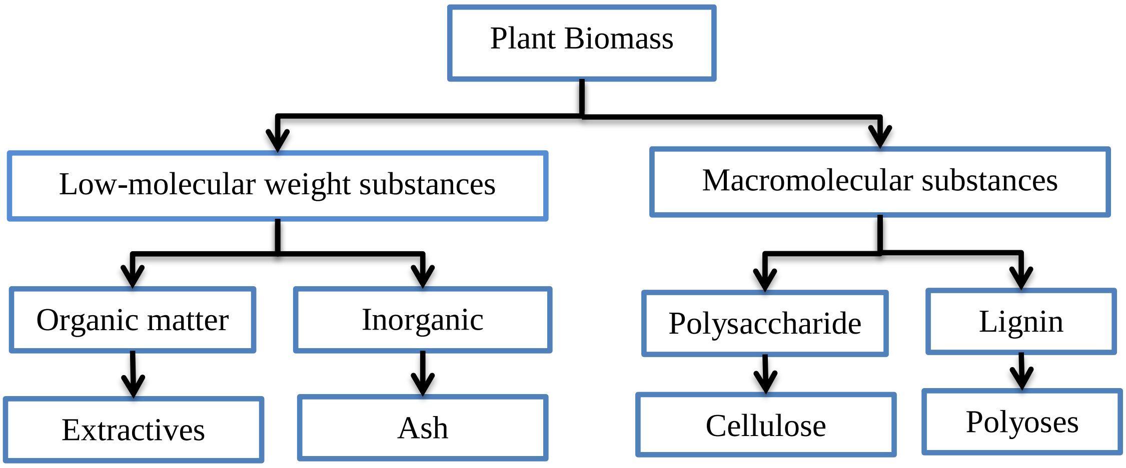

Figure 2.1: Plant biomass composition (Mohan et al., 2006)

Cellulose is a high-molecular-weight polymer which provides structural rigidity to the plants. It consists of linear polymer that makes up about 45% of the dry weight of wood (McKendry, 2002a). In addition, cellulose is a high molecular weight polymer that makes up the fibers in lignocellulosic materials and its degradation start anywhere from 240–350°C because of high resistance of its crystalline structure to thermal depolymerisation owns to its strength (Mohan et al., 2006). The water held in the amorphous regions of the cellulosic wall rupture the structure and then converted into steam as a result of thermal treatment (Tumuluru et al., 2011).

Hemicellulose is a complex carbohydrate polymer with a lower molecular weight than cellulose and makes up 25-30% of total dry weight of wood. In contrast to cellulose, hemicelluloses are easily hydrolysable and do not form aggregates. Thermal degradation of hemicellulose occurs between 130–260°C, with the majority of weight loss occurring above 180°C (Mohan et al., 2006). Hemicellulose produces less tars and char due to its low degradation temperatures range compared to that of the cellulose (Tumuluru et al., 2012a).

Lignin is the most abundant polymer in nature. Lignin is an unstructured and highly branched polymer that fills the spaces in the cell wall between cellulose, hemicellulose, and pectin components (Mohan et al., 2006). It is covalently bonded to hemicellulose and thereby exhibits mechanical strength on the cell wall. It is relatively hydrophobic and aromatic in nature and decomposes between 280°C and 500°C when subjected to a thermal treatment. Lignin is difficult to dehydrate and thus converts to more char than cellulose or hemicelluloses (Tumuluru et al., 2012a).

2.1.2 Energy Conversion Methods

Biomass fuel can be classified into three types namely wood fuels, agriculture fuels and municipal by products. The conversion of biomass into energy can be defined into several different methods. The three main categories of conversion processes are thermo-chemical, biochemical, and mechanical. In Figure 2.2 the routes from biomass to fuels and energy is presented. In addition, sources, processing methods, and products are introduced (McKendry, 2002b).

Thermochemical conversion relies on heat and chemical catalyst to synthesize useful secondary energy. This is an attractive option for biomass to energy due to its higher efficiencies, greater versatility as well as wider range of fuel feedstock.

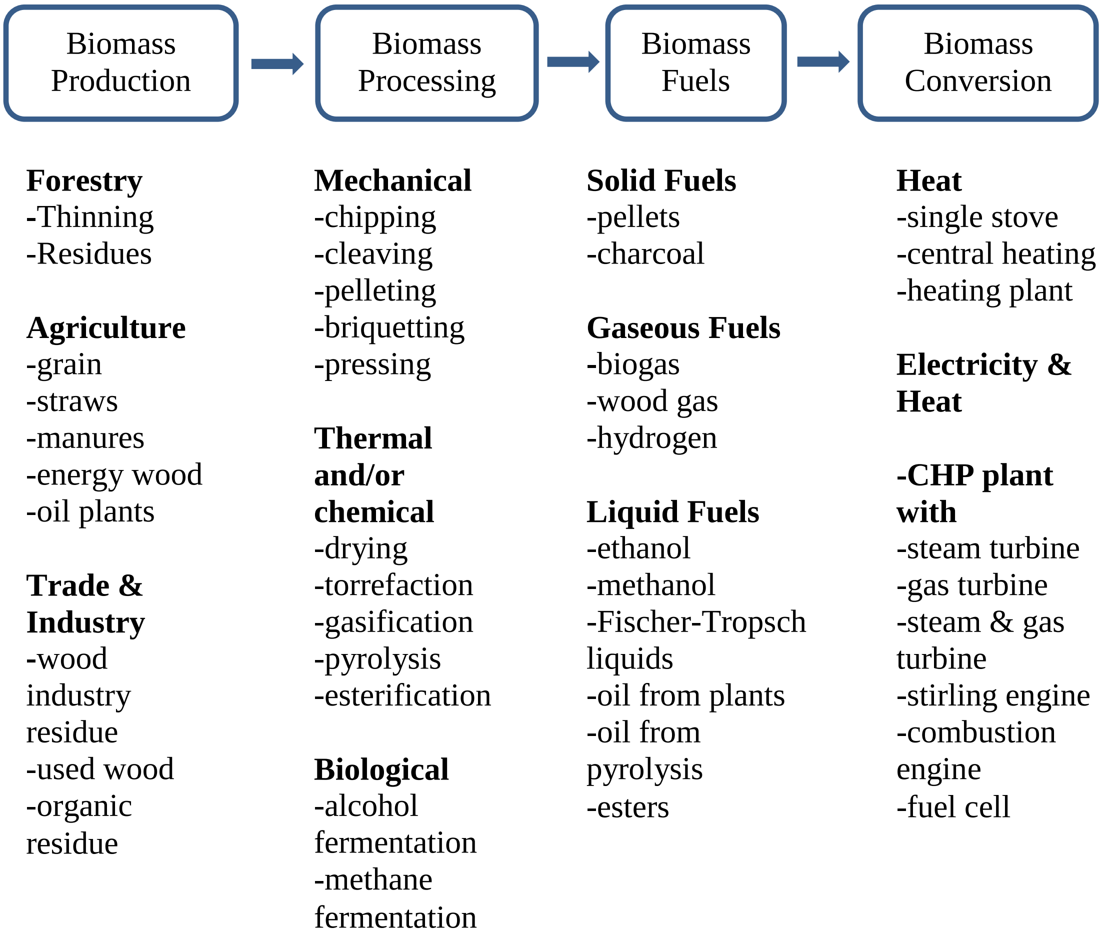

Figure 2.2: From biomass to energy and fuels (McKendry, 2002b)

Biochemical conversion utilizes biological organism and biological catalyst to convert biomass into convenient fuel such as bio-ethanol, biogas and biodiesel (Chew and Doshi, 2011). Thermochemical conversion of biomass compared to biological conversion is a faster process. Another method of biomass conversion is mechanical extraction to obtain secondary fuel by means of physical rolling and crushing of seeds, kernel and fruits (Stelte et al., 2012).

2.1.3 Limitations of Biomass as Fuel

The limitation of raw biomass materials compared to fossil fuel resources are low bulk density, high moisture content, hydrophilic nature, and low calorific value. These inherent problem greatly impact logistics and final energy efficiency on a large scale (Svanberg et al., 2013). Due to its low energy density compared to fossil fuels, very high volume of biomass is needed, which compounds problem associated with storage, transportation, and feed handling at cogeneration, thermochemical, and biochemical conversion plants (Uslu et al., 2008, Bergman, 2005).

The primary limitation of raw biomass is related to its high moisture content. This contributes to reduce in efficiency of the process and increases fuel production costs. High moisture content in biomass leads to natural decomposition, resulting in loss of quality and storage issues such as off-gas emissions (Zanzi Vigouroux et al., 2004). Another consequence of high moisture content is the uncertainty it causes in biomass physical, chemical and microbiological properties. Irregular biomass shapes constitute another issue, especially during feeding in a co-firing or gasification system In addition, biomass has more oxygen than carbon (Tumuluru et al. 2011).

2.2 Gasification

Gasification is a process of converting solid carbonaceous material into combustible gas (medium or low calorific value gas) by thermal decomposition at high temperature with controlled amount of oxygen or steam (Basu, 2010). The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. The producer gas is more versatile in its use than the original solid biomass. It is burnt to produce process heat and steam or used in engines and gas turbines to produce electricity (Soid and Zainal, 2014).

The advantage of gasification is that using the producer gas potentially is more efficient since energy contained in the solid biomass is extracted from gasification compare to direct combustion of original solid biomass fuel. Gasification takes place at elevated temperature 700-900°C which distinguishes it from other biological processes such as anaerobic digestion that produce biogas (Chew and Doshi, 2011).

In order to produce a useable fuel gas, two processes take place in the gasifier. In the first stage pyrolysis or de-volatilization process occur where the volatiles component are released from biomass below 600°C. This process is an endothermic reaction (Kumar et al., 2009). In the second stage, the carbon remaining after pyrolysis is either reacted with steam or hydrogen to form carbon monoxide and hydrogen via endothermic reaction or combusted with air is an exothermic reaction to provide the heat energy required to drive the pyrolysis and gasification reactions (Zainal et al., 2001).

2.2.1 Gasification Gas Composition

Based on literature studied, mainly for downdraft gasification reactor the average composition of gas that can be obtained is: 1.69% O_2, 43.62% N_2, 14.05% H_2, 24.04% CO, 14.66% CO_2, 2.02% CH_4 and C_2H_6 detected as traces in most of the runs with a concentration of 0.01%. The gas composition in producer gas depends on the various factors such as type of biomass fuel, design of gasifier and operating conditions (Zainal et al., 2002).

Besides gas composition, heating value of producer gas obtained depends on the gasifying agent used. Based on the composition obtained from the literature, almost 40%-50% of the gas constituent is composed of non-combustible gas N_2 (Prins, 2005). Although it may be better to use oxygen instead of air for gasification, the cost of producing oxygen could be a limiting factor in this regard. Therefore, in most applications, air is the common gasifying agent that gives a low heating value of producer gas between 4-6 MJ Nm^{-3} whilst medium heating value of 12-18 MJ Nm^{-3} is achieved when oxygen or steam is used (McKendry, 2002c). Table 2.1 shows the heating values obtain from the literature for normal gasification with air as the gasifying agent.

Table 2.1: Heating value of biomass air gasification

Researchers	Heating Value (MJ Nm^{-3})
Zainal et al. (2002)	4.65
Uma et al. (2004)	4.60
Sridhar et al. (2005)	4.50-4.90
Bhoi et al. (2006)	4.33-4.39
Banapurmath and Tewari (2009)	4.19

2.2.2 Factors That Affecting Gasification Process

Producer gas composition varies widely and typically depends based upon the gasifier type, feed stock, feedstock pre-treatment, gasifying medium and operating parameters like temperature, pressure, and nature of interaction between reactants in the gasification process (McKendry, 2002c). The effects of major parameters affecting the producer gas quality are discussed in sections below.

a) Moisture content

Moisture content in biomass, during gasification, increases CO_2 concentration by water-shift reaction which consumes CO and liberates H_2 (Sutton et al., 2001). Since more heat is required for moisture evaporation than the small amount of heat gained due to the exothermic behaviour of the water-shift reaction, thermal energy inside the gasifier reduces when gasifying biomass with higher moisture content. The overall effect is the reduction in calorific value of producer gas because, the small increase in H_2 is not sufficient to compensate the loss of significant amount of CO with increase in moisture content (Sarkar et al., 2014b). When air is used as the gasifying agent, the amount of methane produced is small and stays almost constant with change in moisture content. Thus the temperature decreases inside the gasifier due to moisture also results lower mass conversion efficiency and increase tar content. Decrease in biomass consumption rate is also reported with the increase in moisture content which due to the higher amount of heat necessary for drying the biomass inside the reactor before they can be pyrolyzed. However, some moisture content is always desirable since it enhances steam reforming and helps to crack tar, and at higher temperature, also enhances other reactions such as char gasification (Sivakumar et al., 2012).

b) Equivalence ratio

Equivalence ratio (ER) is the most influential parameter in any gasification process. Low ER increases char formation inside the gasifier. All combustibles products reduce with increase in ER with the formation of higher amount of CO_2 as well as total gas yield, but greatly diminish the heating value of the final producer gas. Zainal et al. (2002) compared the best optimal value for the downdraft gasifier with respect to equivalence ratio using furniture wood and wood chips as feedstock. The effect of equivalence ratio was investigated with conclusion of an optimal ER of 0.38 for the gasifier performance for that particular feedstock. At this ER, CO, CH_4 and calorific value each accomplish their maximum outputs while CO_2 reaches its minimum.

c) Temperature

Increase in temperature reduces tar content as well as decreases char inside the gasifiers. Gas yield increases due to higher tar cracking. Tar cracking temperatures are often reported to be around 1000-1100°C with some dependency on gasifiers design. CO content increases with increase in temperature because endothermic reactions desire higher temperature. An oxidation zone below temperature of 725°C gives significantly lower mass conversion efficiency (Rogel, 2006). Heating values as well as producer gas yield are found to increase due to increase in combustibles, particularly at temperature above 800°C with an increase in operating temperature driven by an external supply of heat in the gasifier for constant ER. The temperature of the reactor is dependent on various factors such as moisture content of the fuel, ER, heat losses from the system and the amount of steam added. The best approach is the proper insulation of the reactor and using waste heat (Bhoi et al., 2006).

d) Biomass type

Biomass elemental composition has a significant effect on producer gas composition. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio and increase when these ratios increase, especially with an increase in hydrogen/carbon ratio (Jenkins et al., 1998). A higher oxygen concentration in biomass needs lower ER for gasification because of its inherent oxygen that will also be available for gasification (Zhang et al., 2007).

e) Particle size

Fixed bed gasifiers have lower biomass feedstock size restrictions compared to fluidized bed gasifiers. Typically, feed sizes less than 51mm and 6mm are suggested for fixed bed and fluidized bed gasifiers respectively (Basu, 2006). The maximum particle size recommended for a conventional downdraft gasifier with throated design is one-eighth of the reactor throat diameter (Warnecke, 2000). The larger particles form bridges avoiding the efficient flow of biomass inside a gasifier while smaller particles obstructs the air/gasifying agent passage creating high pressure drop and consequently can result in gasifier shut-down. Decrease in particle size lessens the heat loss due to radiation and improves the thermal conductivity in the oxidation and reduction zones. Biomass consumption rate is inversely related to particle size. Higher residence time is suggested for larger biomass particle size. Decrease in CO with increase in CO_2 concentration is observed (Yang et al., 2004).

2.2.3 Reactor Design

Gasification reactor can be classified in 2 categories determine based on type of bed design inside the reactor (Warnecke, 2000, Basu, 2010).

i. Fixed bed

    a. Downdraft gasifier
    b. Updraft gasifier
    c. Cross-draft gasifier

ii. Fluidized bed

    a. Bubbling bed (BB) gasifier
    b. Circulating fluidized bed (CFB) gasifier
    c. Entrained-bed gasifier

i) Fixed beds

Fixed bed gasifiers normally have a grate to support the feed material and maintain a stationary reaction zone. They are relatively easy to design and operate, and useful for small and medium scale power and thermal energy uses (Reed and Das, 1998). There is one drawback it is difficult to maintain uniform operating temperatures and ensure allowable gas mixing in the reaction zone. As a result, gas yields can be unpredictable and are not optimal for large-scale power purposes. These are typically two types of fixed bed gasifiers namely updraft and downdraft gasifiers (McKendry, 2002c).

Updraft or counter-current gasifier, the feedstock movement and gasifiying agent move in the opposite directions. Based on Figure 2.3, since the producer gas formed is not forced to pass through the hot high temperature zone, the tar content is high in the producer gas from this gasifier (Basu, 2006). On the other hand, the temperature of producer gas existing from this gasifier is lower around 200°C and hence the thermal efficiency of this kind of gasifier is high (Jain and Goss, 2000). Due to high tar content in the producer gas, a subsequent tar cleaning system is needed, which can become a major investment if the end-process requires tar-free producer gas (Anis and Zainal, 2011).

In a downdraft or co-current gasifier, the feedstock and gasifying agent both move in the same direction. The gases have to pass through a high-temperature zone hence the amount of tar is significantly lower than that in an updraft gasifier (Anis and Zainal, 2011).

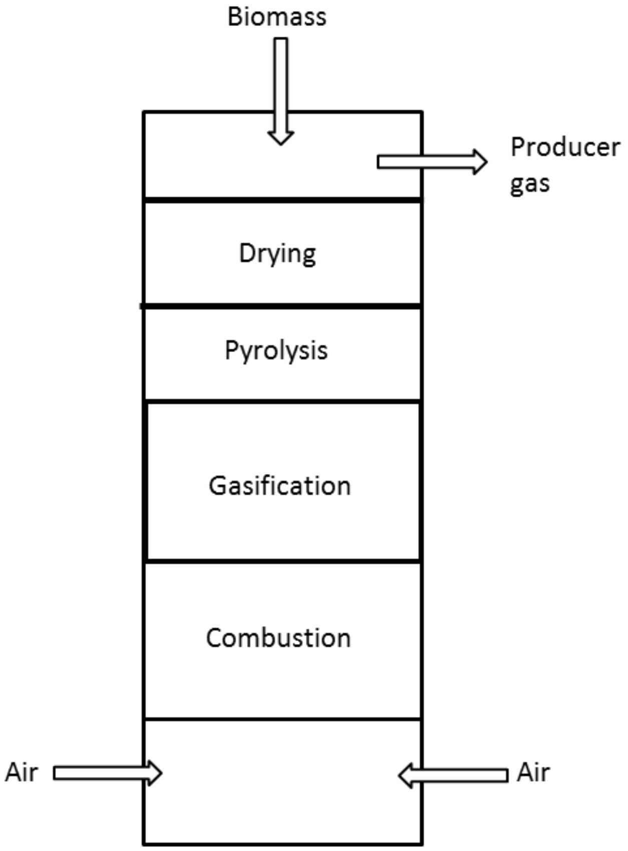

Figure 2.3: Updraft gasifier with gas/biomass flow directions and reactions zones modified from McKendry (2002c)

The particulate content is however higher for downdraft gasifier and the thermal efficiency is lower since producer gas draws an appreciable amount of energy while passing through the high-temperature zone inside the gasifier. Temperature at the oxidation zone is around 900 to 1200°C, and the producer gas leaves the gasifier at a temperature between 200-300°C (Zainal et al., 2002, Jain and Goss, 2000, Dogru et al., 2002).

When comparing downdraft and updraft gasifiers, the downdraft has more advantages in the possibilities of producing gas with low tar content, low ash and particulate concentrations, suitability with various biomass fuels, easy to control, high conversion rate and the most suitably used in combined heat and power generation (Yaliwal et al., 2014).

ii) Fluidized bed gasifier

In fluidized bed gasifiers, feedstock is fluidized with some bed material like sand/silica with a gasifying medium which can be air or steam. Fluidized bed gasifiers can further be classified into two types: bubbling and circulating. Circulating fluidized bed adds one more feature to bubbling bed such that solid material trapped in the gas phase is trapped and recirculated back to the gasification bed (Warnecke, 2000). This provides the significant advantages over the bubbling bed gasifier in terms of mass conversion efficiency and reduces particulate content in the producer gas output.

As shown in Figure 2.4, gasifying agent usually air is blown through a hot bed of inert granular solid material such as sand or ceramic at sufficient velocity to keep these particles in suspended solid (Mahadzir and Zainal, 2011). The biomass fuel are mixed with the hot bed material and heated up to the temperature for gasification, relatively around 750-900°C. The problem with fluidized-bed gasifiers are high tar content up to 500 mg Nm^{-3}, more particulates, incomplete carbon combustion and poor response to load changes (Basu, 2006). The characteristics of each type of gasifiers have been summarized in Table 2.2.

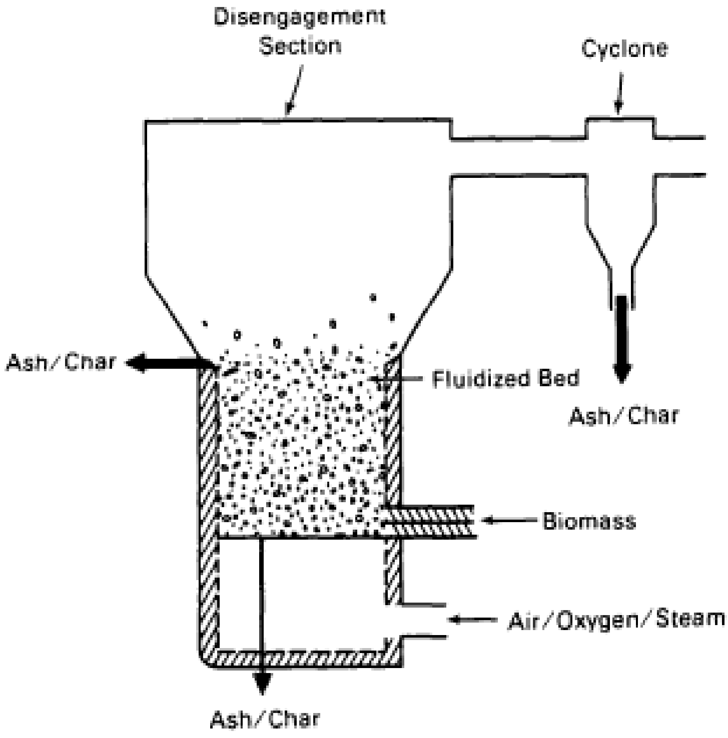

Figure 2.4: Fluidized bed gasifier (Basu, 2006)

2.2.4 Downdraft Gasifier

There are two types of downdraft gasifier throated and throatless gasifiers as shown in Figure 2.5. Throated gasifiers have the advantages of reducing the tar content and thus improving producer gas quality since the high temperature of this narrow zone provides a uniform temperature distribution over the cross section and allows most of the tar contained in the pyrolysis products to crack (Reed and Das, 1998, Basu, 2010). With the temperature at the combustion zone reaching around 900 to 1200°C that is enough to reduce the tar content of producer gas to less than 0.1% by weight or 0.5 g Nm^{-3} (Reed and Das, 1998).

Table 2.2: Various characteristics, properties and differences between types of gasifier (Warnecke, 2000, Basu, 2006, McKendry, 2002c)

Characteristics	**Gasifier Type**		
	Downdraft	Updraft	Fluidized bed
Gasifier size	High 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 distribution		Uniform temperature distribution inside the gasifier
Permissible particle size/ Size sensitivity	< 50 mm/good		< 5 mm/more sensitive to feedstock size
Reaction zone temperature	800-1100°C		800-1000°C
Ability to handle fine particles	Limited		Good
Moisture content	Very Flexible	Flexible	Flexible
Gas exit temperature	600-800°C	250°C	850°C
Tar concentration	Very low (0.001 - 6 g Nm^{-3})	Very high (50 g Nm^{-3})	6 - 12 g Nm^{-3}
Carbon conversion efficiency	Very good		Very good
Thermal efficiency	Very good	Excellent	Very good
LHV of Producer gas	Poor	Poor	Fair
Cold gas efficiency	>80%		>90%
Gas clean-up	High cleaning required	Relatively clean gas	Clean-up required for dust and tar
Dust content in producer gas	High	Low	Higher dust content
Energy requirement for operation	Low		High
Investment	High for energy generation compared to fluidized bed		Lower investment
Process control	Cannot be controlled effectively as fluidized bed		Easy process control
Applications	Small to medium scales		Large scales

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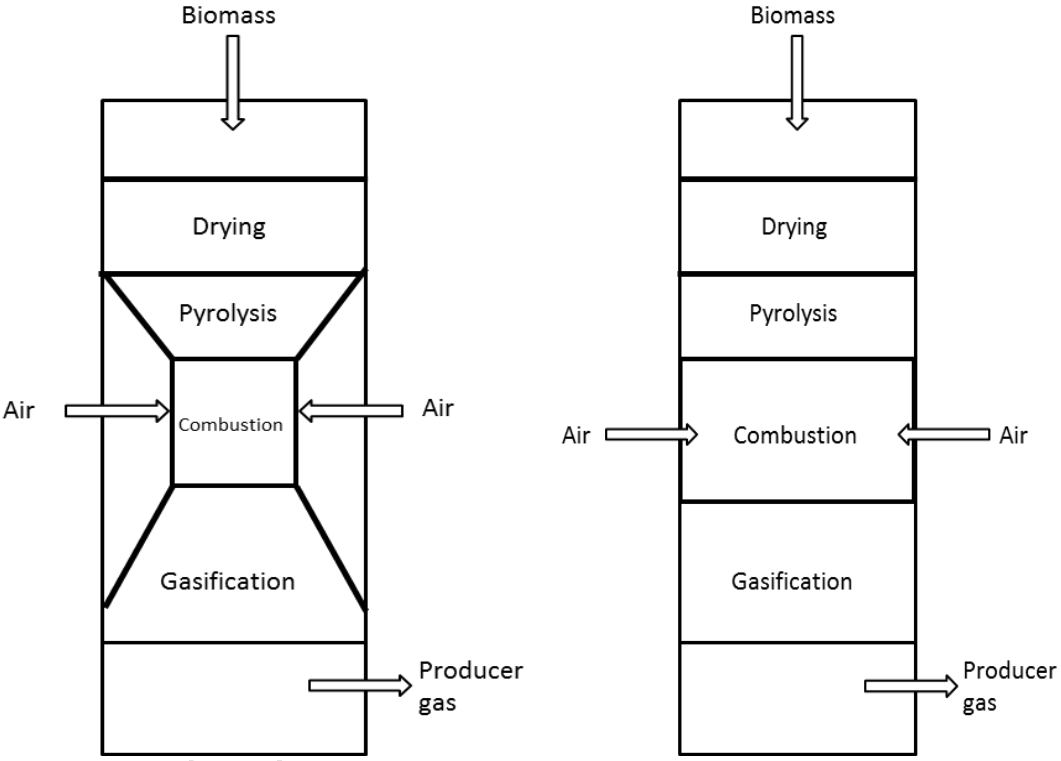

Throated Throatless

Figure 2.5: Throated and throatless fixed bed downdraft gasifier with gas/biomass flow directions and reactions zones. Modified from Basu (2010).

In throatless gasifiers there is no constriction in the gasifier vessel. The throatless design allows unrestricted movement of the biomass down the gasifier, which is not possible in the throated type. This feature can avoid bridging or channelling, which might occur in the throated type (Jain and Goss, 2000).

2.2.5 Gasifier Performance

Throughout the gasification process, various factors such as properties of biomass fuel, particle size, gasifiying agent, temperature, pressure, equivalence ratio, and type of gasifier are the main parameters that affect the performance of a biomass gasifier. This is usually characterized by the quantity and quality of the producer gas that is generated. The heating value and cold gas efficiency are the essential parameters in determining the amount of biomass converted into gas and the quality of the producer gas (Jain and Goss, 2000, Reed and Das, 1998, Basu, 2010) . Cold gas efficiency (η_{cg}) can be defined as the content of energy in producer gas with comparison to that of biomass fuel as expressed below:

$$\eta_{cg} = \frac{LHV_{PG}Q_{PG}}{LHV_b \dot{m}_b} \times 100 \qquad 2.1$$

Where:

LHV_{PG} = lower heating value of the producer gas (MJ Nm^{-3})

Q_{pg} = volumetric flow rate of the producer gas (Nm^3 h^{-1})

LHV_b = lower heating value of the biomass fuel (MJ kg^{-1})

$\dot{m}_b$ = mass flow rate of the biomass fuel (kg h^{-1})

LHV_{PG} can be calculated and is dependent on the percentage volume fraction of H_2, CO, and CH_4 as follow:

$$LHV_{PG} = x_{H_2}LHV_{H_2} + x_{CO}LHV_{CO} + x_{CH_4}LHV_{CH_4} \qquad 2.2$$

Where x is the volume fraction of each gas and the LHV of each gas is 10.757, 12.641 and 35.787 MJ Nm^{-3} for H_2, CO and CH_4 as respectively.

The equivalence ratio (ER) for gasification can be defined as actual air/fuel ratio to stoichiometric air/fuel ratio of biomass combustion, as shown in the following equation:

$$ER = \frac{(Air/Fuel)_{actual}}{(Air/Fuel)_{stoichiometric}} \qquad 2.3$$

Therefore, the air/fuel equivalence ratio for each run of gasifier can be calculated based on the following equation (Zainal et al., 2001):

$$ER = \frac{(flow\ rate\ of\ air\ supply)\ x\ (duration\ of\ time)}{(mass\ input\ of\ wood) x\ (stoichiometric\ air\ flow\ per\ kg\ of\ fuel)} \qquad 2.4$$

Table 2.3 represent the association of few parameters from different gasifiers. The table illustrates the types of gasifier as well as heat output and the different gas compositions dependent on the fuel moisture whereas the LHV of producer gas for all gasifier in the table are fairly related (Van Paasen et al., 2002, Morf, 2001, Bridgwater, 2003).

Table 2.3: Association of few parameters from different gasifiers (Van Paasen et al., 2002, Morf, 2001, Bridgwater, 2003)

Parameter	**Unit**	**Fixed Bed**		**Fluidized Bed**	
		Updraft	Downdraft	Bubbling	Circulating
Typical Heat Output	kW_{th}	1.0-10.0	100.0-1.0	<25.0	<100.0
Fuel moisture	wt.% (daf)	52	6	14	15
CO2	vol%	10.0	11.5	16.7	15.0
CO	vol%	20.0	22.5	15.8	15.4
H2	vol%	14.0	21.0	9.3	14.8
CH4	vol%	2.5	1.5	3.8	4.2
LHV	MJ Nm^{-3}	4.9	5.6	4.4	5.0
Particles	g Nm^{-3}	0.1-0.5	0.1-1	1-10	20-60
Tar	g Nm^{-3}	50-150	0.5-2	1-23	7-10

daf: dry and ash-free basis