EFFECT OF WATER INJECTION INSIDE A DOUBLE WALLED THROATLESS DOWNDRAFT GASIFIER FOR IMPROVING PRODUCER GAS QUALITY

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UNIVERSITI SAINS MALAYSIA
2015

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by

SHAZRUL NIZAM BIN AMAT SAZALI

**Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science**

July 2015

ACKNOWLEDGEMENT

All praises to Allah the Almighty for giving me the chance and strength to complete this thesis. First of all, I would like to express my deepest gratitude to my parents, Amat Sazali Abu Hassan and Rahilah Ishak, for their endless support and encouragement to finish my master degree which enables me to stay focused in finishing my master in time.

I would like to express my deepest appreciation to my supervisor, Prof. Dr. Zainal Alimuddin Zainal Alauddin who had supported me throughout this project with his valuable guidance, advice and patience. It was my greatest luck to pursue my study under his supervision.

Special thanks to the biomass energy research group for their outstanding guidance and knowledge. Their helps had driven me to finish this project until the end. My appreciation also goes to all the School of Mechanical Engineering staffs for their kindness and support in this research study.

Last but not least, I would like to thank all my friends for their encouragement and support for me to finish my master degree. I wish to express my sense of gratitude to one and all who, directly or indirectly, have lent their helpful hand in this research. May Allah bless all of you.

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LIST OF ABBREVIATIONS

C_2H_6	Ethane
CCM	Cubic centimeter per minute
CH_4	Methane
C_nH_m	Hydrocarbons lower than tar compounds
C_nH_x	Tar
CO	Carbon monoxide
CO_2	Carbon dioxide
DWTD	Double walled throatless downdraft gasifier
ER	Equivalence ratio
GC	Gas chromatograph
H_2	Hydrogen
H_2O	Water or steam
He	Helium
HHV	Higher heating value
LHV	Lower heating value
LPM	Litre per minute
MC	Moisture content
N_2	Nitrogen
PAH	Polycyclic aromatic hydrocarbon
S/B	Steam to biomass ratio
TGA	Thermogravimetric analyzer

LIST OF SYMBOLS

C_E	Energy balance closure
C_m	Mass balance closure
E_i	Energy input (MJ/h)
E_o	Energy ouput (MJ/h)
m_i	Mass input
m_o	Mass output
$\dot{m}_{biomass}$	Mass flow rate of biomass
$\dot{m}_{steam}$	Mass flow rate of steam
M_{air}	Mass flow rate of air (kg/h)
M_{mc}	Mass flow rate of moisture content (kg/h)
M_{pg}	Mass flow rate of producer gas (kg/h)
MW_{pg}	Molecular weight of producer gas (kg/kmol)
R	Ideal gas constant (0.08205 m^3.atm/kmol.K)
V_{air}	Volumetric flow rate of dry air (m^3/h)
V_{pg}	Volumetric flow rate of dry producer gas (m^3/h)
η_{CG}	Cold gas efficiency

KESAN PENYUNTIKAN AIR KE DALAM PENGGAS ALIR TURUN DUA DINDING UNTUK PENAMBAHBAIKAN KUALITI GAS PENGELUAR

ABSTRAK

Potensi biojisim sebagai tenaga alternatif telah terbukti berikutan tenaga yang tidak boleh diperbaharui seperti bahan api fosil yang semakin berkurang dan semakin mahal. Kualiti gas pengeluar yang menggunakan udara sebagai ejen penggasan mempunyai nilai pemanasan yang rendah dengan lingkungan antara 4-5 MJ/Nm^3. Penggasan stim dapat menghasilkan gas pengeluar yang lebih berkualiti jika dibandingkan dengan proses penggasan biasa yang hanya menggunakan udara, tetapi penjana stim yang menggunakan banyak kuasa diperlukan untuk menghasilkan stim. Kaedah penyuntikan air telah dicadangkan dalam usaha untuk menambahbaik kualiti gas pengeluar dengan cara menaikkan kandungan hidrogen dan nilai pemanasan gas pengeluar tersebut. Penggas yang digunakan di dalam eksperimen ini ialah penggas alir turun dua dinding. Air akan disuntik ke dalam penggas. Secara teori, air yang disuntik ke dalam penggas akan bertukar menjadi stim kesan daripada haba dari dinding penggas tersebut. Jadi, nisbah stim kepada biojisim (S/B) diperkenalkan bagi mengkaji jumlah optimum untuk air yang diperlukan bagi satu jumlah spesifik biojisim yang dapat menghasilkan kualiti optimum untuk gas pengeluar. Perbandingan komposisi dan nilai pemanasan bagi gas pengeluar antara eksperimen dengan dan tanpa penyuntikan air telah dianalisis dan dikira dengan bantuan gas kromatografi. Nisbah S/B optimum 0.2 telah menghasilkan gas pengeluar dengan nilai pemanasan 4.87 MJ/Nm^3 dengan kenaikan prestasi keseluruhan sebanyak 10%. Beberapa nisbah S/B yang berbeza telah dikaji dalam lingkungan 0.1 ke 0.3. Nisbah

S/B yang lebih tinggi dari 0.25 akan menyebabkan kesan yang kurang baik terhadap kualiti gas pengeluar. Kesan nisbah (S/B) terhadap tar juga disiasat di dalam eksperimen ini. Nisbah S/B yang semakin tinggi akan menghasilkan gas pengeluar dengan kandungan tar yang lebih rendah. Nisbah S/B optimum 0.2 telah menghasilkan hasilan tar sebanyak 0.675 g/m^3, di mana pengurangan sebanyak 4.26% telah berlaku.

EFFECT OF WATER INJECTION INSIDE A DOUBLE WALLED THROATLESS DOWNDRAFT GASIFIER FOR IMPROVING PRODUCER GAS QUALITY

ABSTRACT

Biomass had been proven of its potential as an alternative energy since non-renewable energy such as fossil fuels are undergoing depletion and price increase. The quality of the producer gas using air as gasifying agent has a relatively low heating value of 4-5 MJ/Nm^3. Steam gasification produces better producer gas in quality compared to normal air gasification but requires a steam generator which uses a lot of power to generate the steam. Water injection method had been proposed in order to enhance the producer gas quality by increasing the hydrogen content and heating value thus directly increases the quality of the producer gas. A double walled throatless downdraft gasifier (DWTD) was used in the study. Water is injected into the annulus of the gasifier that separates the bed and the air supply. Theoretically, the water injected into the gasifier will be converted into superheated steam by the heat from the wall of the gasifier. So, steam to biomass (S/B) ratio has been introduced to investigate the optimum amount of water needed to be injected for a specific amount of biomass that produces the optimum quality of producer gas. Comparisons were made on the composition and heating value of the producer gas with and without water injection which were analyzed and calculated with the aid of a gas chromatograph. Heating value of the producer gas with the optimum S/B ratio of 0.2 was found to be 4.87 MJ/Nm^3 with approximately 10% increment in the overall gas performance. Various S/B ratios were investigated in this study with the range from

0.1 to 0.3. However, as S/B ratio goes higher than 0.25, it results adversely to the quality of the producer gas. The effect of water injection on tar was also investigated in this experiment. Higher S/B ratio had resulted in lower tar concentration in the producer gas. The optimum S/B ratio of 0.2 has given a tar yield of 0.675 g/m^3, which is 4.26% reduction.

CHAPTER 1

INTRODUCTION

1.1 Background

Energy can be divided into two main categories: renewable and non-renewable energy. Non-renewable energy comes from resource with a finite amount which take a very long time to form. Fossil fuels such as coal and petroleum were acknowledged to serve in many purposes for a long time. However, with the increasing price and the rate of depletion of fossil fuels, there has been a trend towards the use of alternative energy. Renewable energy had been an important focus point since its potential as an alternative energy. Renewable energy studies seem to be more intense every day. The renewable energy is suitable as the alternative energy since they are naturally replenished at a constant rate, energy sources like hydropower, geothermal, solar and wind can be taken as examples (Li et al, 2015).

Petroleum, coal and natural gas are the most important primary energy sources with more than 90% of total world's primary energy consumption in the year of 2009 as shown in Table 1.1. Renewable energy like biomass material has not been fully exploited but shows some promises in the energy field. From year to year, the technology for renewable energy systems are being developed and commercialized on larger scale in order to make it cheaper and more reliable. This is very important in order to overcome energy crisis in the future.

Table 1.1: Total world's primary energy consumption in 2009 (EIA, 2010)

Type of Energy	Fuel	Percentage (%)
Non-renewable energy	Petroleum	37.0
	Natural gas	24.0
	Coal	23.0
	Nuclear	8.0
Renewable energy	Biomass	4.3
	Geothermal and hydropower	3.1
	Solar and wind	0.6

1.2 Biomass as Energy Sources

Biomass is one of renewable energy resources. It is defined as an organic substance or any material derived from living organisms. It is the fourth largest energy resources in the world and is abundant in Malaysia. The abundance of these resources makes it a major focus in finding the alternative energy sources. Forest products and their residues, agricultural crops and their residues, woody wastes, municipal solid wastes, animal manure, aquatic plants and algae are the most common biomass materials. Energy utilization from agricultural wastes seems to be very attractive due to bio-resource sustainability, environmental concerns and economic reflection. Other than that, forest residues are also becoming the main resources for biomass. Malaysia produces large volume of biomass and has a huge potential in renewable energy. Other than agricultural wastes and forest residues, municipal solid waste or simply MSW is another type of biomass sources which is typically known as 'trash' or 'garbage' by the public. This is the reason why biomass material is abundant and easy to get. Another major advantage of biomass over other renewable energy is that if it is not been used as an energy source, it will becomes a pollutant and environmental hazard.

Being an eco-friendly process is another big plus for biomass energy sources since any potential of reducing the global warming effect is considered to be a major issue in finding alternative energy sources. Carbon dioxide is a major contributor to the global warming effect. Carbon from fuels that react with oxygen in the air produces carbon dioxide which causes environmental issues such as global warming and climate change. By comparing both fossil fuels and biomass, the potential can be seen in the usage of biomass as an alternative energy in order to reduce the greenhouse effect since the production of carbon dioxide in biomass combustion is a carbon neutral process.

Continuous efforts and researches which focused on biomass to extract the energy from it had been done. Numerous biomass materials turned out to be useful energy sources and products. Figure 1.1 shows the scope of biomass initiatives as renewable energy.

There are several processes in order to make use of the biomass as energy source but it can be divided into two main processes which are biological and thermochemical processes. Thermochemical processes are the main focus here which involves combustion, gasification, pyrolysis and liquefaction. Thermochemical processes typically have high throughputs which mean large scale processes can be done. Furthermore, thermochemical processes can operate on any biomass form which differs from the biological processes that can only operate on some of the components of biomass.

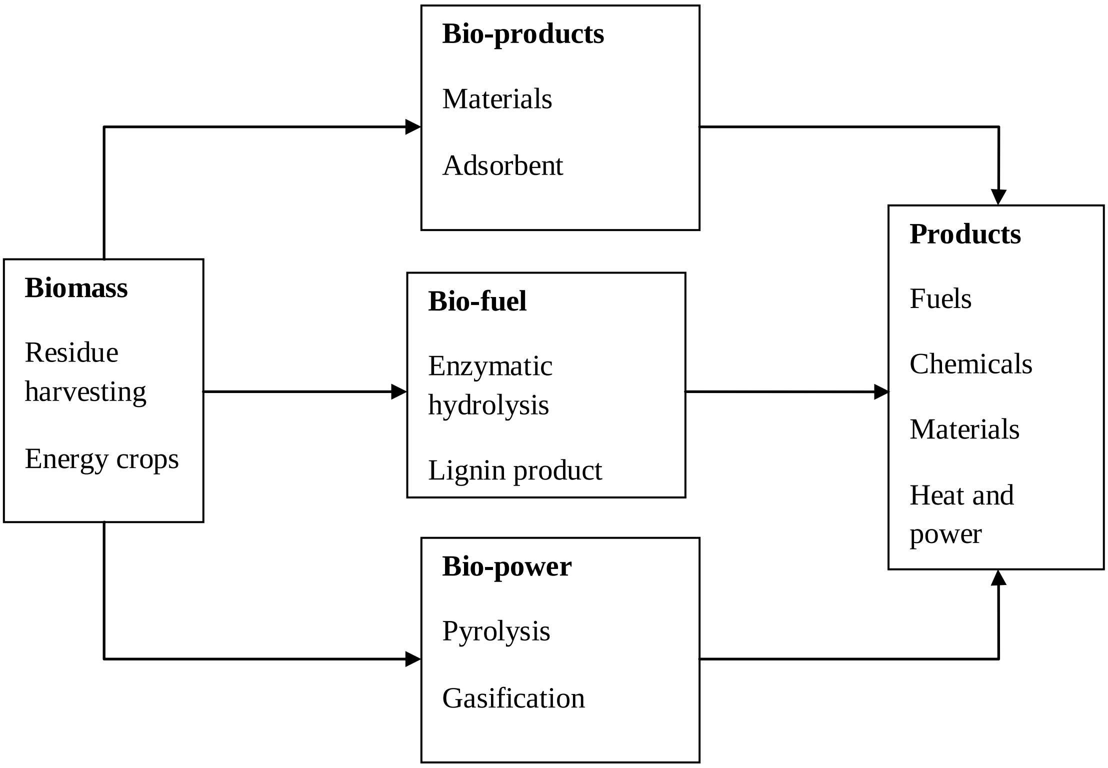

Figure 1.1: Biomass initiatives as renewable energy (Mekhilef et al, 2011)

Pyrolysis, gasification and combustion process are the most common energy conversion process of biomass. In gasification process, the biomass material will undergo a process that converts it into gaseous fuel known as producer gas. Some of the usage of producer gas is for both compression and spark ignition internal combustion engines and gas turbines to generate electricity and as a substitute for furnace oil in direct heating applications and also to produce methanol. The advantage of gasification is that it is more efficient compared to pyrolysis and combustion. This is because the producer gas can be combusted at higher temperatures. Plus, gasification is better in term of emission control compared to direct combustion that produces pollutants and contaminants.

The reactor used for gasification process is called a gasifier that converts solid fuel into producer gas. It takes place at temperature of about 800-900^{o}C with a controlled amount of gasifying agent: air, oxygen or steam. The controlled amount of air for example is the reason for the differences between combustion and gasification. In biomass combustion, excess oxygen is supplied for complete combustion. The combustion products generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. Meanwhile, in biomass gasification, the controlled amount of air supplied results in incomplete combustion of biomass where the product of gasification is a combustible gas called producer gas, which consists of carbon monoxide (CO), hydrogen (H_2) and traces of methane (CH_4), nitrogen (N_2) and carbon dioxide (CO_2). Non-useful products like tar and ash are also produced and need to be removed (Balat et al, 2009).

1.3 Problem Statement

Gasifier which uses air as gasifying agent produces combustible gas with relatively low heating value which is in the range of 4-5 MJ/Nm^3 (Zainal et al, 2002). The heating value of producer gas is directly related to the quality of the producer gas itself. The quality of the producer gas can be increased by using steam or oxygen instead of air as the gasifying agent. However, the steam and oxygen as gasifying agents require additional energy which causes reduced efficiency in energy consumption. Other solutions are needed in order to enhance the quality of the producer gas produced.

The heat loss through the wall of the gasifier is a wasted energy that could be recovered for other purposes. Water will be injected into the gasifier and theoretically, the heat from the wall of the gasifier will convert the water into superheated steam. Hence, steam will mix with air to become the gasifying agent which apparently will increase the quality of the producer gas. Wall of bricks are built around the gasifier to conserve the heat from the wall of the gasifier. The amount of water injected will be varied to obtain the optimum steam-to-biomass (S/B) ratio which will give optimum heating value of the producer gas.

1.4 Objective of Study

The objectives of the study are as the following:

i. To design and develop the water injection system in the double walled throatless downdraft gasifier.
ii. To study the optimum steam-to-biomass (S/B) ratio in order to obtain the optimum quality of the producer gas.
iii. To study the effect of water injection on the formation of tar.
iv. To improve the overall efficiency of the gasification process with the use of water injection system.

1.5 Scope of Research

Development of the experimental rig will be the initial step in the study. The experimental rig will consist of two main systems: gasification and water injection systems. The steam to biomass ratio will be studied based on its effect on the heating value of the producer gas and also the formation of tar. These two outcomes will determine the quality of the producer gas. The parameters which give the optimum condition for the whole system will be finalized to find the optimum quality of the producer gas that can be produced in this study.

1.6 Thesis Outline

The thesis is divided into five chapters which consist of introduction, literature review, methodology, results and discussion and conclusions. Details of the thesis outline are described as follow. Chapter 1 briefly describes the ability of biomass as energy sources. The problem statement of this study is also provided. Next, the objectives and the scope of this study are highlighted. The outline 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 detail of biomass properties is explained. Next is the literature review on the biomass gasification process and the operating parameters. Types of reactors are also presented in this chapter which is reviewed to give the detail specification required for the gasification process. Finally, a summary of the literature review are presented at the end.

Chapter 3 describes the details of experimental set-up for the gasification process. The materials of this study are described which is followed by the equipment for the sampling and analyses of products including gases, wood pellet and tar. The descriptions of process procedures are also included.

Chapter 4 presents the results and discussion of the experimental study. The characteristics of gasifier system and temperature profile are explained in this chapter. The product of the gasification process which are producer gas and tar are also 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 was used as an energy source for a very long time and it is the oldest form of energy. It is one of the renewable energy and has been a promising alternative energy since it is abundant worldwide. Biomass is the fourth largest energy sources at the moment, right after petroleum, coal and natural gas. Biomass resources contribute 15% of the primary energy consumption in the world (Bhattacharya et al, 2012). Depletion of fossil fuel sources is really in terrifying stage and had forced all nations around the globe to introduce alternative sources of energy. Biomass appears to be a viable option in this matter since its potential had been known.

Biomass is a non-fossilized and biodegradable organic material which comes from plants, animals and microorganisms. It also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the organic fractions of industrial and municipal wastes (Bhavanam and Sastry, 2011). Sheth and Babu (2009) used the term biomass to describe all biologically produced matter and as a name to all living matter on earth. Biomass energy is derived from the plant sources, waste from agricultural and forestry processes and industrial, human or animal wastes. Biomass can also be defined as a naturally available plant material. It is derived via photosynthesis process to produce carbohydrates, which form the building blocks of biomass (Panwar and Salvi, 2011). Wenni et al (2014) stated that biomass mainly consists of lignin cellulose and hemicelluloses. This brings up the next idea by Balu and Chung (2012) which stated that biomass can be divided into cellulosic and lignocellulosic biomass. Cellulosic is basically food crops while lignocellulosic biomass is a non-food based biomass which comes from the fibrous, woody and generally inedible portion of the plants that are mostly composed by hemicelluloses and lignin. Meanwhile, based on Ruiz et al (2013), biomass is declared as a heterogeneous mixture of organic matter and to a lesser extent, inorganic matter, including several solid and liquid phases with different contents.

2.1.1 Biomass as an Energy Source

Awareness of the depletion of the conventional energy sources has causes many countries to shift their energy policy towards renewable energy. The abundant supplies of biomass resources have attracted attentions to utilize it as an alternative energy. Moreover, another reason of using biomass as an energy sources is that its abundance will become pollutant if they were not used. Table 2.1 shows the amount of each type of biomass component in Malaysia in the year of 2009 and also their potential electricity generated. The electricity power is calculated based on the calorific value of each component (Shafie et al, 2012).

Other than its abundance, other advantages of utilizing biomass as an energy sources are bio-resources sustainability, economic reflection and environmental concerns. Fossil fuel combustion has been known to have an adverse effect on the environment. Global warming had been a major issue nowadays which leads to extreme change in the world’s climate. Being an eco-friendly source of energy had given a major advantage to biomass. Biomass energy is the most potential energy source to overcome the expanding needs of energy and also at the same time preserving the environment.

Table 2.1: Biomass sources in Malaysia, 2009 (Shafie et al, 2012)

Biomass component	**Calorific value (MJ/kg)**	**Electricity generated (GWh)**
Palm oil residue		
Shell	23.51	5792.13
Fiber	22.07	1578.19
Empty fruit bunch	21.52	46346.15
Coconut residue		
Shell	20.15	0.84
Bunches	19.60	0.02
Frond	19.60	0.11
Husk	19.60	0.18
Paddy residue		
Rice husk	15.80	0.51
Rice straw	14.71	1.59
Sugarcane		
Bagasse	18.11	0.21
Top and trashier	17.45	0.21

2.1.2 Limitations of Biomass Resources

Biomass resources has also counter several challenges. Some biomass properties are inconvenient which limits it characteristics as a fuel. Stelt et al (2011) stated that biomass has high oxygen content, high moisture content, low calorific value and a hydrophilic nature. The high oxygen content will results in the production of smokes during combustion process while high moisture content will affect the quality of the final product of the process. Low calorific value will result in high volume of biomass needed to give the same amount of energy produced by a given amount of fossil fuel. Additional logistic costs, energy uses and material losses will be an issue regarding this matter (Uslu et al, 2006). In a bigger picture, the use of biomass will gives limitation to land, water and competition with food production.

In other aspects, the limitation of biomass is not just on the biomass itself as a fuel. Other challenges can also occur in technical, economic or policy constraint. Shafie et al (2012) summarized these constraints for biomass based power generation in Malaysia as in Table 2.2.

Table 2.2: Constraints for biomass based power generation in Malaysia (Shafie et al, 2012)

Author/s	**Year**	**Limitation**		
		Technical	**Financial**	**Policy**
Koh and Hoi	2003	No local expertise for efficient biomass energy conversion	High energy production	Lacking of awareness regarding the renewable energy consumption
Jaafar et al	2003	Reliable of supply	-Lack of financial supports -Very expensive due to lacking of economies of scale in renewable energy projects	Poor perception about the potential supply of renewable energy at the national level
Mohammed and Lee	2006	-Development of conversion technology is not establish -No commercialization on large scale in renewable energy generation	Renewable energy generation cost is competitive	Lacking of reliable information on the potential supply of renewable energy at the national level
Ahmad et al	2011	Lack of technical knowledge has lead to poor quality product	Malaysia provide enormous subsidy that results in a cheap electric price from national grid	Lack of interest from commercial investors
Sovakool and Drupady	2011	-Lack of new technology -Insufficient education, training and sharing experience among all stakeholders	-Low electricity tariffs for renewable power producers -Unfamiliarity and resistance from financial bakers	-Lack of strongly implemented national policy frameworks -Flaws in program design

Table 2.2: Continued

Author/s	Year	Limitation		
		Technical	**Financial**	**Policy**
Saidur et al	2011	No local manufacturers for the efficient conversion of biomass to energy	-High energy production cost -No subsidy for energy production from renewable energy sources -Lacking of financial mechanism	-No national strategy given to encourage biomass for energy use -Lacking of information and awareness among different national agencies
Ali et al	2012	Lacking of local expertise in efficient handling equipment	Market price of renewable energy system will be high to compensate the cost of research and development	Unattractive to potential inventor due to available of cheaper conventional energy sources

2.1.3 Biomass Energy Conversion Process

The useful energy is needed to be extracted from the biomass by converting it into easily combustible material. The processes involved in order to convert biomass into useful energy can be divided into two main processes which are biological and thermochemical conversion processes. In thermochemical conversion process, there are three processes that can be used to extract energy from dry biomass: combustion, pyrolysis and gasification (Olgun et al, 2011). Figure 2.1 shows the thermochemical conversion of biomass (McKendry, 2002).

Combustion process is the most commonly used conversion process compared to pyrolysis and gasification, since the latter two are still under developmental stages. Direct combustion will convert biomass energy into heat and it is then used to generate electricity. It is generally an open fire cooking and heating which had been used for thousands of years. Any type of biomass resources can be used in combustion but popular practices is to use biomass with moisture content less than 50% (Shafie et al, 2012). Another thermochemical conversion process that can be used to produce energy from biomass is pyrolysis which is defined as the decomposition of biomass material at elevated temperatures with no air or oxygen supplied. This process will yield a variety of energy rich products with the product mix depends on the temperature of the process. More char are produced than gas or oil at low temperatures.

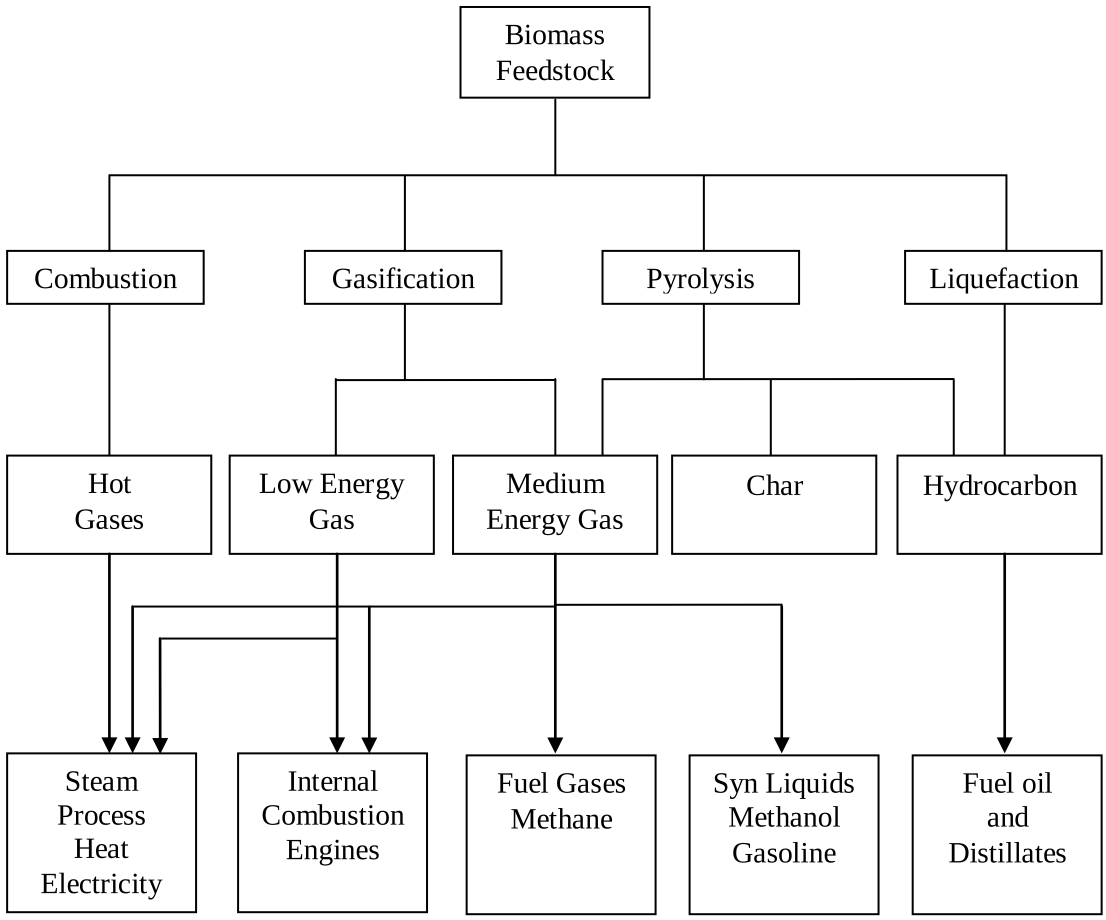

Figure 2.1: Biomass thermochemical conversion process (McKendry, 2002)

Last but not least is the gasification process which is a thermochemical breakdown of the biomass material which is similar to pyrolysis, except that gasification occurs in limited presence of air or oxygen. The product of gasification is producer gas, a gaseous component which consists mainly of hydrogen and carbon monoxide. Gasification is the intermediate step of thermochemical conversion between pyrolysis and combustion (Shafie et al, 2012).

2.2 Biomass Gasification

Gasification is one of the thermochemical processes that can be used to extract the energy from solid biomass. It converts the biomass materials into gaseous components which is called producer gas, with the aid of gasifying agent (air, steam or oxygen). The producer gas also comes with a fraction of char and ash as the product of the gasification process. The producer gas is a mixture of carbon monoxide, hydrogen, oxygen, methane, carbon dioxide and nitrogen. In order to optimize the gas production, the gasification process is carried out at high temperatures between 500 - 1400 ^{o}C with a range of pressure that runs from atmospheric pressure to 33 bar (Ruiz et al, 2012; Balat et al, 2009). Gasification can be stated as an intermediate stage between pyrolysis and combustion, with the main differences of the amount of oxygen supplied to the process.

There are four stages in gasification but Basu (2010) stated that the limit between them is unclear since these stages overlap each other. The four stages are heating and drying, pyrolysis, oxidation and gasification stages. Ruiz et al (2013) has described a detailed explanation for each stage. Heating and drying of the biomass material is an early step before the material can be put into the gasifier. The moisture content of biomass should be in between 10 to 15% since the moisture in the biomass will require energy to vaporize the water and that energy cannot be recovered. Next is the pyrolysis stage where char, a solid carbonaceous waste formed along with gases. The third step is oxidation process of some gases, steam and char by a gasifying agent. This stage will generate energy for the gasification and pyrolysis reactions. Finally, the char that was produced during pyrolysis will be gasified to create the final product which is the producer gas. Chemistry of the gasification process is shown as the following (Ruiz et al, 2013).

Char or gasification reactions

$C + CO_2 \longleftrightarrow 2CO$ (+172 kJ/mol) 2.1

$C + H_2O \longleftrightarrow CO + H_2$ (+131 kJ/mol) 2.2

$C + 2H_2 \longleftrightarrow CH_4$ (-74.8 kJ/mol) 2.3

$C + 0.5O_2 \longrightarrow CO$ (-111 kJ/mol) 2.4

Oxidation reactions

$C + O_2 \longrightarrow CO_2$ (-394 kJ/mol) 2.5

$CO + 0.5O_2 \longrightarrow CO_2$ (-284 kJ/mol) 2.6

$CH_4 + 2O_2 \longleftrightarrow 2CO$ (+172 kJ/mol) 2.7

$H_2 + 0.5O_2 \longrightarrow H_2O$ (-242 kJ/mol) 2.8

Shift reactions

$CO + H_2O \longleftrightarrow CO_2 + H_2$ (-41.2 kJ/mol) 2.9

Methanization reactions

$2CO + 2H_2 \longrightarrow CH_4 + CO_2$ (-247 kJ/mol) 2.10

$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$ (-206 kJ/mol) 2.11

$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$ (-165 kJ/mol) 2.12

Steam reactions

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \ (+206 \text{ kJ/mol}) \qquad 2.13$$

$$CH_4 + 0.5O_2 \longrightarrow CO + 2H_2 \ (-36 \text{ kJ/mol}) \qquad 2.14$$

Gasification has attracted great interests in the energy conversion sector compared to other processes. This is because of the versatility of gasification that can be used to produce producer gas, hydrogen or other liquid fuels which therefore meet the demand for electricity and thermal energy (Ruiz et al, 2013). One of the traits of gasification is that its final product is in gaseous form. The advantages of gas as a fuel over liquid or solid are as following:

i. gases burn with a higher efficiency than solid or liquid forms
ii. they can be readily transported in pipelines
iii. they have higher rate of heat release
iv. the rate of energy output is easily controlled and adjustable
v. less fouling of the heat exchange equipment occurs
vi. very low particulate emissions occur
vii. less gaseous pollutants
viii. gaseous fuels with good energy potential can be used for electrical power generation.

There are several applications that come from the biomass gasification. Balat et al (2009) summarized the products that can be obtained from gasification process in Figure 2.2. The producer gas can be burned to generate heat or electricity and also serve in the synthesis of transportation fuels or chemicals. Besides, it is mainly used as fuel gas in an internal combustion engine for power production. Rajvanshi (1986) verified this by mentioning the main applications of biomass gasification are as shaft power systems, direct heat applications and chemical production. Martinez et al (2012) studied the application of producer gas using internal combustion engines. Reciprocating internal combustion engine or simply known as RICE, has been used with downdraft gasifiers which create a viable technology for small scale heat and power generation.

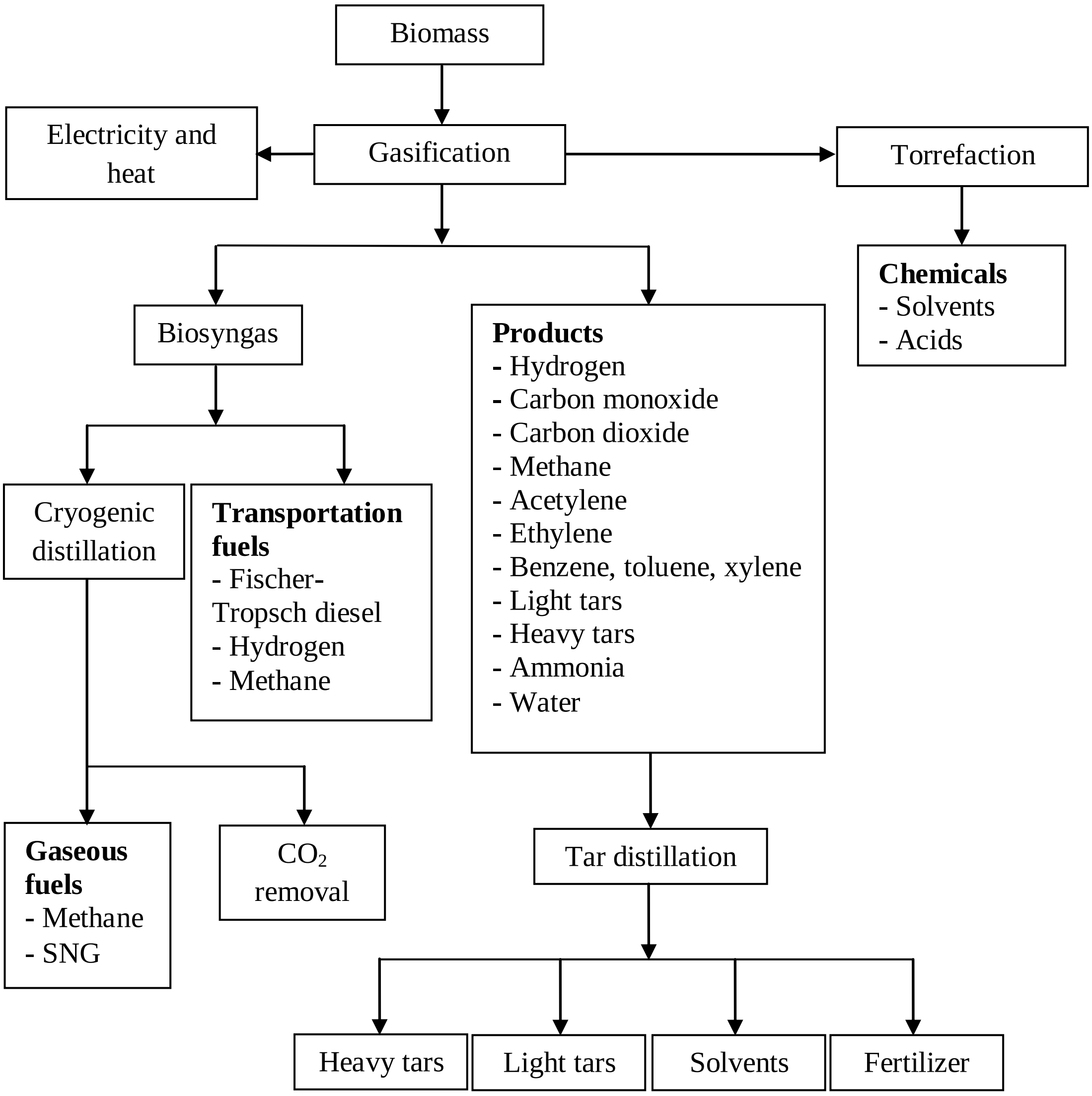

Figure 2.2: Products from gasification process (Balat et al, 2009)

2.2.1 Producer Gas

Producer gas is a combustible gas which consists of hydrogen, oxygen, nitrogen, carbon monoxide, methane and carbon dioxide. The average gas composition is 14.05% hydrogen, 1.69% oxygen, 43.62% nitrogen, 24.04% carbon monoxide, 2.02% methane and 14.66% carbon dioxide. There are also traces of ethane with a concentration of 0.01%. However, this number will vary for every different experimental runs since the composition of the producer gas depends on several factors such as biomass fuel type, gasifier design and operation conditions (Zainal et al, 2002).

Heating value is another characteristic of the producer gas that can be studied. Heating value is the term used to describe the amount of heat produced by the complete combustion for a certain amount of fuel. The higher the heating value of the producer gas, the better the quality is. The heating value of the producer gas depends on the type of gasifying agent used. Low heating value is obtained when air is used as the gasifying agent with a value somewhere in between of 4-5 MJ/Nm^3. When oxygen or steam is used to replace air as the gasifying agent, medium heating value can be achieved. Lim and Lee (2014) reported calorific value of 10-14 MJ/Nm^3 for steam gasification. Meanwhile, Basu (2010) stated that the heating value for steam gasification is 10-18 MJ/Nm^3 while 12-28 MJ/Nm^3 for oxygen gasification. Heating values obtained from several literatures for normal gasification process with air as the gasifying agent is shown in Table 2.3.

Table 2.3: Heating value of producer gas with air as gasifying agent from several literatures

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

2.2.2 Types of Gasification Process

The type of gasification process is determined by the types of gasifying agents used in the gasification process. Air gasification is the simplest and cheapest route to gasification process and is the most widely used gasification process. However, the gas product from air gasification have a relatively low quality, with its heating value is only about 4-5 MJ/Nm^3. This phenomenon is due to the high volume of nitrogen in air dilutes the gas produced since nitrogen does not react with biomass, thus producing a low energy gas, which is suitable for operation of boilers and engines.

Oxygen and steam gasification produces medium energy gas, which is suitable for pipeline distribution. For steam gasification, it can also reduce the high heat of reaction other than increasing the gas quality. The heating value problem can easily be eliminated by using oxygen or steam as the gasifying agent if only no additional energy is required to generate oxygen or steam. However, the generator to produce either steam or oxygen does need the additional energy thus affecting the overall efficiency of the whole process. The solution for this was discussed in the problem statement, which is by the introduction of water injection method which theoretically, adequate to increase the quality of the producer gas.

Hydrogen and carbon monoxide content in gaseous product is very important since it will determine the quality of the gas. Lv et al (2007) had done a research to study the comparison of gas composition between air gasification and oxygen/steam gasification. The content of hydrogen and carbon monoxide composition in the producer gas is compared between these two types of gasification. As expected, the results came with the content of both hydrogen and carbon monoxide to be higher in oxygen/steam gasification compared to air gasification. This phenomenon happens because of two factors: nitrogen amount is almost zero at the condition of oxygen/steam gasification and the presence of steam that gives deeper reforming reactions of biomass gasification gases. Based on Pinto et al (2003), the presence of oxygen in steam gasification is more effective in reducing tars and hydrocarbons concentrations through combustion reactions.

2.2.3 Parameters of Gasification Process

There are several parameters that govern the gasification of biomass. These parameters should be controlled in order to achieve a constant quality of the gasification process. There are quite a number of parameters involved in the biomass gasification, with only the major parameters involved are discussed.

2.2.3.1 Moisture Content

One of the characteristic of biomass is its high moisture. Different type of biomass will have different value of moisture content; with some biomass can be as high as 90%. Table 2.4 shows the moisture content of some biomass fuels used in the gasification process. Based on Bhavanam and Sastry (2011), the biomass consumption rate for a gasification process decreases with an increasing value of moisture content of the biomass used. This is due to the amount of energy needed for drying process in increase thus limiting the energy for pyrolysis process. In conclusion, high amount of moisture in a biomass fuels will affect the operation of the whole gasification system and also the quality of the producer gas. However, this constraint of moisture content are dependent on the gasifier used, some types of gasifier may tolerate higher moisture content than other types. Sharma (2008) had seen the effect of moisture content in the biomass to the producer gas composition. With an increase of moisture content in the biomass, percentage of carbon monoxide decreases while hydrogen and carbon dioxide percentages increase. The moisture content also affects the heating value of the gas produced and also the gasification efficiency. However, some moisture in the biomass may gives some advantages to the biomass gasification since it enhances steam reforming and helps to crack tar. It also enhances some reactions at higher temperature. (Sivakumar et al, 2012).

Table 2.4: Moisture content of different biomass types in gasification process (Bhavanam and Sastry, 2011)

Biomass	Moisture content (wt%)	Biomass	Moisture content (wt%)
Corn stalks	40-60	Wood bark	30-60
Wheat straw	8-20	Saw dust	25-55
Rice straw	50-80	Food waste	70
Rice husk	7-10	RDF pellets	25-35
Dairy cattle manure	88	Bagasse	40-50

2.2.3.2 Equivalence Ratio

The equivalence ratio is the ratio between the actual air-fuel ratio for the current process and the stoichiometric air-fuel ratio for complete combustion. Increasing the equivalence ratio will increase the temperature inside the gasifier since there is more oxygen per volume of biomass for combustion process. In term of the producer gas composition, higher equivalence ratio value will results in a higher carbon dioxide percentage but decrease the percentage for both hydrogen and carbon monoxide. Thus, the heating value of the producer gas will also decrease. However, increasing the equivalence ratio has its own upside since it can reduce tar formation since a higher amount of oxygen to react with the volatiles (Bhavanam and Sastry, 2011). The optimum equivalence ratio for gasification falls within the range of 0.2 to 0.4, which enables the formation of tars and char to be controlled. (Ruiz et al, 2012). Bhavanam and Sastry (2011) and Martinez et al (2012) also state the same value for optimum range of the equivalence ratio.

2.2.3.3 Feedstock

The biomass that will be used as fuels inside the gasifier may have different characteristics in term of type, size and shape. The type of biomass refers to the materials of the biomass. It may be wood chips or saw dust pellet. Size and shape of the feedstock plays an important role in the biomass gasification process. The smaller the feed, the faster the gasification process becomes. Moreover, if the feed is too small, the path of the gasifying agent inside the gasifier will be blocked and will cause high pressure drop. Consequently, the high pressure drop can results in the shut-down of the gasifier. Problems will also occur if the feedstock is too large since bridges can form, hence affecting the flow and the process inside the gasifier.

2.2.3.4 Temperature

Temperature is one of the most important parameters in the biomass gasification process and needs to be controlled accurately. Operating the gasifier at high temperature will reduce the amount of tar formation during the gasification. Since the chemical reactions involved in the gasification process is also affected, the composition of tar will also change. Other than that, high operating temperature will also give higher process efficiency since higher amount of char is being converted into gas. Combustible gas content, gas yield, hydrogen and heating value also increased significantly with the increase in temperature. However, reduction of ash requires lower temperatures and thus limiting the gasification temperatures to only 750 ^{o}C (Bhavanam and Sastry, 2011). In terms of the producer gas composition, percentages of carbon monoxide increases at elevated operating temperature while carbon dioxide and methane percentage shows reduction in value. Amount of water formed is also decreases with increasing operating temperature (Ruiz et al, 2013).

2.3 Biomass Gasifiers

Gasifiers are the reactors used to convert the biomass material into combustible gases which is simply known as the producer gas. It is where the biomass fuels and gasifying agent are mixed for the gasification process to occur. There are two main types of application for the gasifier which are the power gasifier and the heat gasifiers. The gasification systems are connected to an internal combustion engine or reciprocating engine in the power gasifier which will produce shaft power that can be used for running a compressor or generating electricity. Heat gasifiers are widely