DEVELOPMENT AND CHARACTERIZATION OF A SMALL-SCALE SELF-SUSTAINED STEAM-BIOMASS GASIFIER

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DEVELOPMENT AND CHARACTERIZATION OF A SMALL-SCALE SELF-SUSTAINED STEAM-BIOMASS GASIFIER

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABBREVIATIONS

H_2	Hydrogen
N_2	Nitrogen
O_2	Oxygen
CH_4	Methane
CO_2	Carbon dioxide gas
CO	Carbon monoxide gas
HHV	High heating value
LHV	Low heating value
LPG	Liquid petroleum gas
PG	Producer Gas
S/B	Steam to Biomass Ratio
USM	University Sains Malaysia

LIST OF SYMBOLS

$\dot{m}_{\text{steam}}$	Mass flow rate of steam (kg/s)
$\dot{m}_{\text{biomass}}$	Mass flow rate of biomass (kg/s)
kg	Kilogram
g	Gram
cm	Centimeter
mm	Millimeter
min	Minute
s	Second
ml	Millilitre
MJ/m^3	Mega joule per cubic meter
MJ/Nm^3	Mega joule per normal cubic meter
kJ/mol	Kilo joule per mole

ABSTRAK

Dunia sedang berkembang ke arah tenaga boleh diperbaharui berikutan peningkatan penggunaan tenaga dan kebimbangan alam sekitar. Biomas mewakili sumber tenaga boleh diperbaharui yang semakin meningkat. Penukaran termokimia dan biologi adalah dua kaedah yang paling biasa untuk menukar biomas kepada tenaga. Gasifikasi adalah proses termokimia yang biasanya melibatkan menukar bahan api pepejal kepada bahan api gas yang dikenali sebagai gas pengeluar (PG) dengan menggunakan ejen gasifikasi. Penggunaan udara sebagai ejen gasifikasi akan menghasilkan gas pengeluar berkualiti rendah (PG) dengan pengeluaran hidrogen yang rendah. Stim akan digunakan sebagai ejen gasifikasi untuk mengatasi isu ini kerana stim boleh memperkayakan pengeluaran hidrogen. Biomass stim gasifier yang mampan dibina termasuk bekalan pemanasan sendiri dari bahagian terbakar gas pengeluar. Oleh itu, penggunaan stim sebagai ejen gasifikasi telah diterokai dalam penyelidikan ini. Stim dihasilkan menggunakan dandang stim elektrik. Proses prestasi gasifier dan gasifikasi dicirikan berdasarkan beberapa parameter seperti suhu saluran gasifier, suhu pada grate gasifier, kadar aliran stim, nisbah wap kepada biomas, penggunaan biomas, dan komposisi gas pengeluar. Nisbah stim kepada biomass yang digunakan dalam eksperimen ini adalah dalam julat 2.82 hingga 9.92. Bagi ciri-ciri gasifier, suhu tertinggi yang direkodkan pada grate adalah 369 ºC pada kadar aliran stim 21.88 g/min. 21.88 g/min kadar aliran stim memberikan suhu tertinggi pada grate untuk gasifikasi stim, dan kadar aliran biomas adalah tinggi pada 52.78 g/min . Pengeluaran H_2 tertinggi yang dicapai adalah pada nisbah S/B sebanyak 4.81, dengan HHV PG yang diperolehi adalah 4.68 MJ/Nm^3.

ABSTRACT

The world is evolving toward renewable energy due to an increase in energy consumption and environmental concerns. Biomass represents a growing potential source of renewable energy. Thermochemical and biological conversions are the two most common methods for converting biomass to energy. Gasification is a thermochemical process that typically involves converting solid fuel into gaseous fuel known as producer gas (PG) by using a gasifying agent. The utilisation of air as a gasifying agent will produce a low quality producer gas (PG) with low hydrogen production. Steam will be used as a gasifying agent to overcome this issue because steam can enrich hydrogen production. A self-sustained steam biomass gasifier was built which includes self-heating supply from the burning part of the producer gas. Thus, the use of steam as gasification agents was explored in this research. Steam was generated using an electric steam boiler. The gasifier performance and gasification processes were characterised based on several parameters such as gasifier outlet temperature, gasifier grate temperature, steam flow rate, steam-to-biomass ratio, biomass consumption, and producer gas composition. The steam to biomass ratio used in this experiment was in the range of 2.82 to 9.92. As for the gasifier characterisation, the highest temperature recorded at the grate was 369 ºC at a steam flow rate of 21.88 g/min. 21.88 g/min of steam flow rate gave the highest temperature at the grate for steam gasification, and the biomass flow rate was high at 52.78 g/min flow rate. The highest H_2 production achieved was at S/B ratio of 4.81, with HHV of PG obtained was 4.68 MJ/Nm^3.

CHAPTER 1

INTRODUCTION

1.1 Background

Global climate change is rapidly affecting the environment and sustainability. Climate change that occurs due to carbon dioxide emission is currently debated around the world. The higher consumption of fossil fuels leads to higher emissions of greenhouse gases. The use of non-renewable energy sources, including coal, fossil fuels, coal, and petroleum is very high around the world, and this kind of source of energy will eventually run out in a few years. Our dependency on non-renewable energy has increased throughout the years. Figure 1.1 show the fossil fuel consumption by fuel type in Malaysia from 1965 to 2019 (Hannah Ritchie and Max Roser 2017).

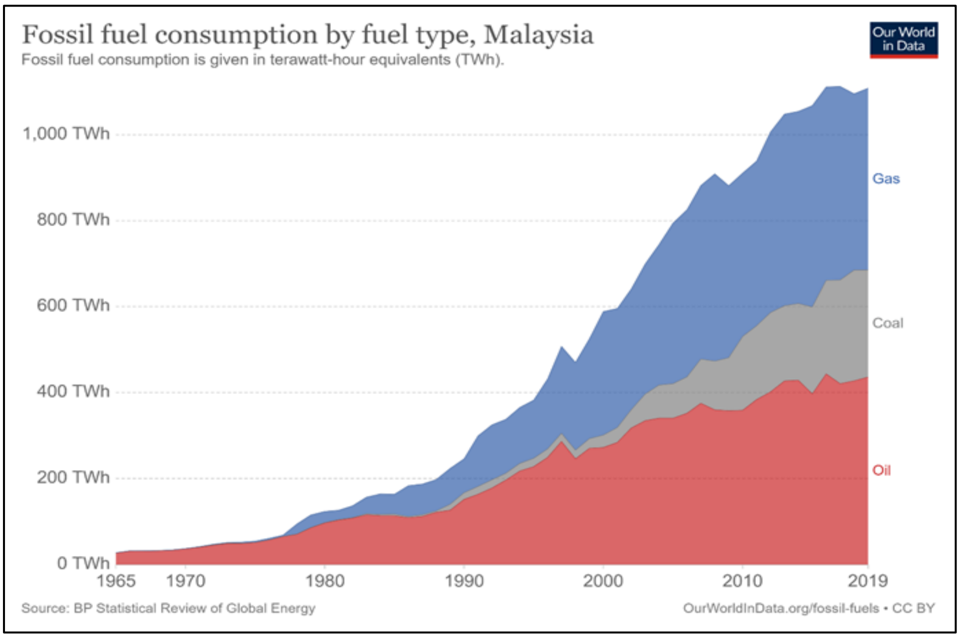

Figure 1.1: Fossil fuel consumption by fuel type in Malaysia from 1965 to 2019 (Hannah Ritchie and Max Roser 2017)

It can be observed that consumption has risen over the years and has proven that we are dependent on fossil fuels. In addition to that, global climate change and global warming is occurring caused by the emission of greenhouse gases which is influenced by the burning of the fossil fuels (Hannah Ritchie and Max Roser 2017).

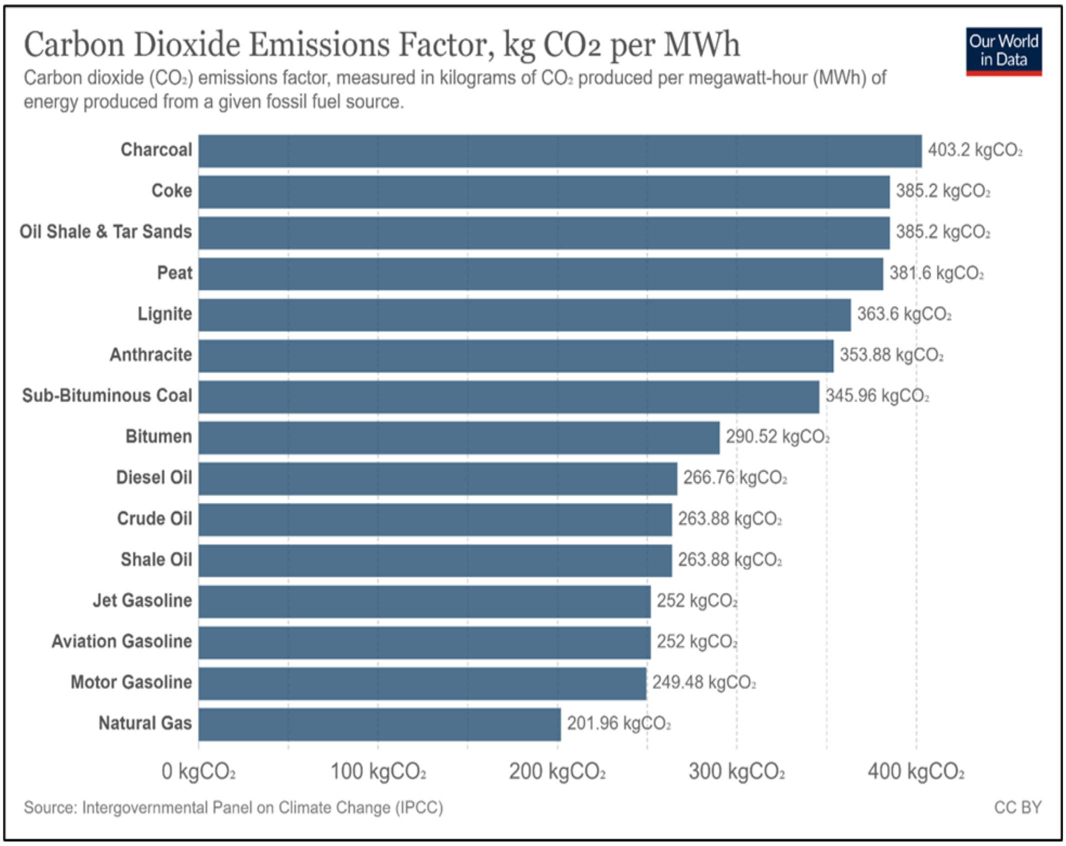

Figure 1.2: CO_2 emissions for the various types of fossil fuels (Hannah Ritchie and Max Roser 2017)

Figure 1.2 shows the CO_2 emissions for the various types of fossil fuel in kg that is produced per megawatt-hour (MWh). In addition to being the main source for world energy production, the process of generating energy from fossil fuels produces a large amount of CO_2 (Hannah Ritchie and Max Roser 2017). If this process persists, it will not stop the decline of fossil fuels source and global warming will not slow down. Therefore, this issue has become crucial and has encouraged researchers to seek renewable energy sources as alternatives to fossil fuel replacement. Biomass, hydropower, wind, solar, and geothermal energy are types of renewable energy sources that are regenerated by nature and are environmentally friendly due to their less emissions. Production of rich hydrogen gas from the renewable energy source is considered the most vital green energy technology due to its high energy content and prospective applications in the power, energy, chemical, and transportation sectors (Kuo et al. 2021).

1.2 Biomass

Biomass represents a growing potential source of renewable energy. Biomass has been shown to be effective for its multiple uses and abundance among the available sources. Biomass is also known as a carbon-neutral energy source. Palm oil plantations currently cover millions of hectares of land in Malaysia, producing massive amounts of biomass (Zahraee et al. 2019).The energy production sector can be transformed in ways where sustainable energy system can be produced when biomass energy is used effectively.

As an energy source, biomass can be utilized through a several processes that can be split into two major processes known as thermo-chemical and biological conversion. The thermo-chemical process includes combustion, pyrolysis, liquefication and gasification (Bhaskar and Pandey 2015). Table 1.1 shows the types and simple definitions of thermo-chemical conversion of biomass.

Table 1.1: Type of thermo-chemical conversion and definition (Pandey et al. 2015)

Type of Process	**Definition**
Combustion	Burning biomass in the presence of oxygen
Pyrolysis	Conversion biomass in the absence of oxygen
Liquefication	Conversion of biomass in the presence of water or solvent
Gasification	Conversion of biomass with partial oxidation

Combustion is a common technique for converting biomass into energy. It converts energy by heating or burning biomass in the presence of oxygen. However, incomplete combustion releases carbon monoxide (CO) as a by-product that is very harmful to the atmosphere. Therefore, knowing the correct amount of air and fuel mixture is essential for complete combustion. The combustion process consists of three process which are drying, pyrolysis and reduction (Susastriawan, Saptoadi, and Purnomo 2017).

1.2.1 Biomass gasification

Biomass is widely used for the process of biomass gasification. The process of gasification typically involves the conversion of solid fuel into gaseous fuel by using a gasifying agent. Gasifying agent could be steam, air and CO_2. The output of this process is called either producer gas (PG) or syngas (synthesis gas) which is a gaseous fuel and is combustible. PG and hydrogen generated at high temperatures in the range of 650-1200°C where the partial oxidation of biomass occurred as is an endothermic reaction(Shahbaz et al. 2017).

Gasifier used as a reactor for the gasification process where the conversion of biomass fuel to gaseous fuel takes place. PG is a combination of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2). The producer gas also contains hydrocarbons with a low molecular weight such as propane and ethane, and hydrocarbons with a high molecular weight such as tars, that condense at temperatures between 250 and 300 °C.

The use of steam gasification has advantages over the use of air gasification. Steam gasification is more feasible than air gasification when it comes to lower formation of tar and good quality of PG composition (Shahbaz et al. 2017). The gas produced by biomass gasification can be utilised to generate power in turbines and internal combustion engines.

1.3 Problem Statement

At present, there is a various investigation conducted on the effects of the operating conditions to the performance and efficiency of gasification using different types of biomass in a downdraft gasifier. The production of good quality producer gas is still the most challenging topic. A large amount of tar produced in the producer gas is also a big problem in biomass gasification which causes the blocking and fouling of corrosion of equipment such as engines and turbines. The other downside of air-gasification is the high dilution with N_2 and CO_2 that can contaminate up to 60% of the producer gas. Steam-gasification solves this problem by eliminating the source of the dilution. However, steam reaction with biomass is fully endothermic and requires external heat source to occur. Research studies on steam-gasification only use small lab-scale due to the difficulty in up-scaling the reactor with efficient heat supply to achieve economically viable production. Therefore, in this research, a small-scale gasifier with a self-heating supply will be developed and will be characterized the gasifier performance in terms of the gas quality at different steam/biomass (S/B) ratios. The producer gas will be analyzed via gas chromatography.

1.4 Objectives of Project

The specific objectives of this research are:

1) To develop a small-scale steam gasifier with self-heating supply from the burning part of the producer gas.
2) To characterize the gasifier performance in terms of the gas quality at different steam/biomass (S/B) ratios.

1.5 Scope of Project

This study involves experimental study on the biomass gasification system and characterization of the gasifier performance in terms of the gas quality by using steam gasification system. The data collected from the experiment conducted are used for the characterization of the gasifier performance in terms of the gas quality at different steam/biomass (S/B) ratios. The very first step in this study is the development of the gasifier setup. As for the biomass, the wood pellet is used in this experiment since it has the high heating value. The steam will be injected into the gasifier chamber at different steam flow rate. The thermocouple scanner will used to measure and the record the temperature at the outlet exhaust gas. The PG sampling was collected into gas sampling bag by using the cooling coil. The producer gas samples will be collected, and the gas composition will be analyzed by using gas chromatography.

1.6 Thesis Outline

The thesis is divided into five chapters which are the introduction, literature review, project methodology, results and discussion and conclusion respectively. Chapter 1 briefly discusses about the fossil fuel depletion and importance of renewable energy resources especially biomass, which has been proven as the best option. A brief introduction on gasification as a thermochemical conversion process for biomass was done which is the process that will be used in this project. In chapter 2, review regarding biomass was done as energy source as well as the various gasification technology and types used to harvest energy from biomass. Research methodology is explained in detail in chapter 3. The apparatus used, system setup, types of measurements done with the specific tools, equations for calculations and experimental methodology are stated in chapter 3 as well. The results obtained and the respective discussions are in chapter 4. This includes the results for gas composition at different steam/biomass ratio for steam gasification. Chapter 5 concludes and summarizes the findings of this project as well as the future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the significance of biomass as a renewable source, as well as several gasification systems that use biomass as fuel and steam gasification are discussed. Several experiments on biomass have been conducted to prove that it can serve as a viable alternative to fossil fuels in terms of energy output. Some of the literature has presented statistics on the reliance on biomass as an energy source through the period. The chemical reaction that occurs in the biomass gasification process is discussed thoroughly from (Situmorang et al. 2020). Biomass gasification for several types of gasifiers, including fluidized bed, updraft, downdraft, and cross draft gasifiers, is thoroughly explored. Some researchers have tested the effects of a different kind of gasifying agent on syngas composition and power generation.

2.2 Biomass

In their research article, (AlNouss, McKay, and Al-Ansari 2020) mentioned that the ongoing global need for energy because of climate change has a significant impact on energy development. Greenhouse gas emissions from a non-renewable energy source such as burning of fossil fuels lead to climate change. This has caused people to increase the utilization of renewable energy to minimize their dependence on non-renewable energy sources like fossil fuels. In this research article, biomass has been shown as a sustainable energy source that can generate power and fuels. The use of biomass as an energy source can reduce carbon emissions by around 20%. The reduction of emission is very vital because it is expected that the current 160 megatons of carbon emissions are predicted to grow about 640 megatons of carbon by 2100. It is mentioned that biomass has a low combustion efficiency based on traditional biomass-based combustion technologies. However, there is some recent development on biomass gasification such as thermochemical conversion technique which able to convert biomass feedstock to a highly combustible gas.

(Hossain, Jewaratnam, and Ganesan 2016) mentioned that biomass is the fourth most plentiful, renewable, and prospective sustainable energy source on the world. Oil palm is a potential source of biomass energy in Indonesia and Malaysia which has resulted in a rise in oil palm plantation. In this research, oil palm waste was used as a biomass feedstock. It mentioned that a fresh fruit bunch (FFB) fabricates 6-7% oil palm shell (OPS), 12-15% oil palm fibre (OPF), 21-23% empty fruit bunches (EFB) of its weight. In 2010, 80 million tonnes of oil palm waste were generated in multiple palm oil factories. The hydrogen (H_2) production was generated through the thermochemical process. In this research, the influence of different variables of thermochemical process includes temperature, biomass to water mass ratio, and catalysts were tested to identify the hydrogen yield.

Based on International Energy Agency's (IEA) World Energy Outlook 2014 (WEO, 2014), the share of renewables in worldwide power generation from biomass would increase from 21% in 2012 to 26% in 2020, reaching around 33% in 2040 (Pacioni et al. 2016).These statistics give intuition into how influential renewable energy sources will be for power generation and other usages especially biomass due to their abundance.(Situmorang et al. 2020) mentioned that biomass contributes around 50% of all renewable sources of energy. Biomass was listed as the 4th largest energy source and contributing 14% of the world’s final energy consumption in 2014. Biomass is also non-fossilized, as it is obtained from plants, animal waste, and algae. The thermochemical and biological processes are the two primary methods for conversion of biomass into energy, according to (Situmorang et al. 2020). The thermochemical process is believed to be highly effective than biological because of its rapid reaction rate and better conversion ability. The thermochemical process involves the use of heat to transform solid biomass into gaseous fuel, while the biological conversion transforms various types of biomass fuels into gaseous and liquid fuels. Figure 2.1 shows the biomass energy conversion pathways for both thermochemical and biological processes.

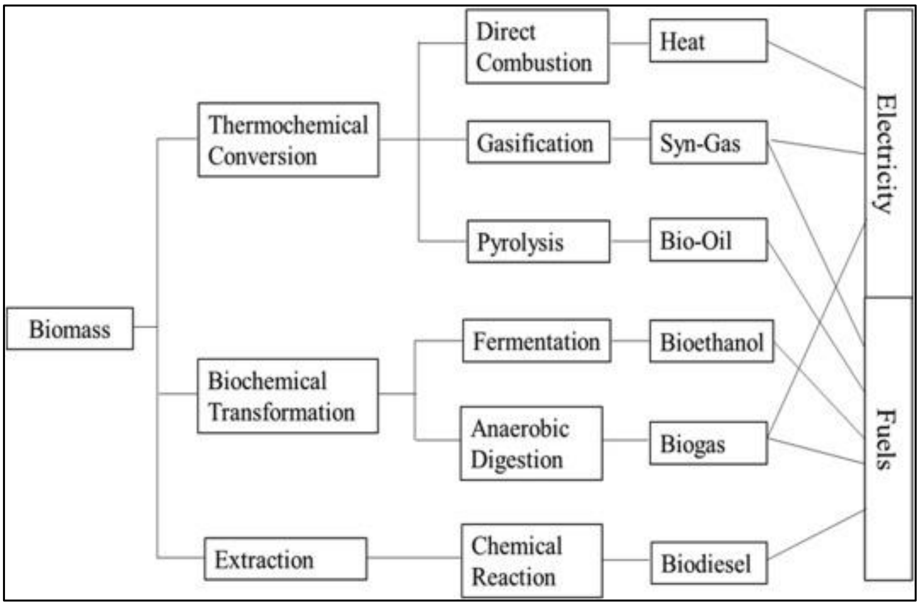

Figure 2.1: Biomass energy conversion (Situmorang et al. 2020)

2.3 Biomass Gasification

Biomass gasification is a thermochemical reaction that converts biomass feedstock into gaseous fuel or PG.(Situmorang et al. 2019) mentioned that, in biomass gasification, gasifying agents such as air, steam, CO_2, or a combination of any of these are used to produce PG, which mostly consists of CO, CO_2, CH_4, H_2, and low amounts of light hydrocarbons. PG can be used as fuels for powering engines and direct heat applications. Thermochemical process is considered to have a high thermal efficiency compared to the direct combustion process as it is the simplest process. Gasification can generate electricity, energy, and synthesis of chemicals, and it has been proven that the emission is very low. The requirement of oxygen is minimum in gasification process as it is not like the direct combustion process which requires excess oxygen (Situmorang et al. 2020). Figure 2.2 illustrates the publications about biomass gasification from 2001 to 2017. The increase in numbers is due to technological developments over the years, which contributed to the development of research for biomass gasification. As a result, the number of journal articles on this technology has increased over the years. It is due to a desire to develop a sustainable energy source as well as a suitable technology or system for making optimal use of energy (AlNouss, McKay, and Al-Ansari 2020).

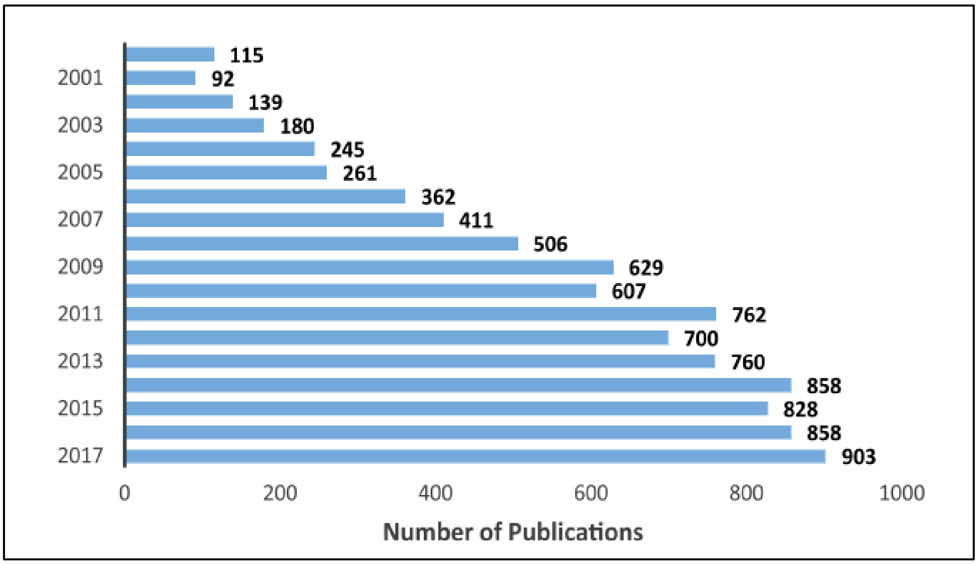

Figure 2.2: Publications regarding biomass gasification (AlNouss, McKay, and Al-Ansari 2020)

In addition to that, (Guan et al. 2016) mentioned that gasification is the most effective for biomass among other thermochemical methods because it produces PG, which can be used to generate power. In this article, the four stages during the biomass gasification process are described and illustrated briefly.

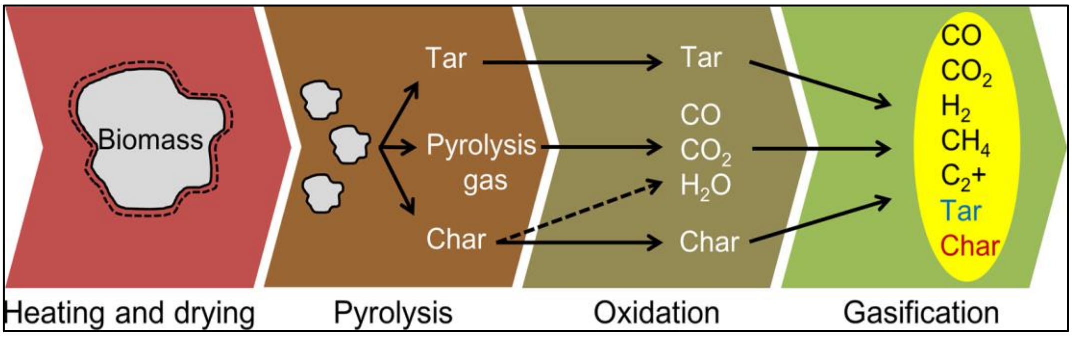

Figure 2.3: Biomass Gasification Process (Guan et al. 2016)

Figure 2.3 illustrates the main processes that occur during biomass gasification:

i. Biomass drying and heating

The moisture content of biomass must be less than 15% to ensure the biomass gasification process occurs efficiently. Therefore, to allow the biomass to have low moisture content, the temperature must be around 200°C.

ii. Pyrolysis

This process takes place at temperature range from 150 and 900 °C in the absence of air. During this processes, hemicellulose, cellulose and lignin in biomass breakdown into char and gases that are volatiles with having different molecular weights. Some volatiles form a black viscous liquid of the hydrocarbons which is called tar, after cooling down to room temperature.

iii. Oxidation

This process takes place at temperatures above 700 °C. The product from pyrolysis will either completely oxidized or partially oxidized with the assist of oxygen. In this process, heat will supply for the subsequent gasification reactions because oxidation is an exothermic reaction.

iv. Gasification/Reduction

Gasification or reduction takes place when the temperature reaches above 800 °C, which causes the char to react with gasifying agents like steam and oxygen to produce PG.

2.3.1 Biomass Gasification Reactions

In biomass gasification, there are few types of reactions, which are carbon, hydrogasification, oxidation, water shift, methanization, and steam reactions. All these reactions summarise the process of gasification for air steam gasification, as mentioned by (Situmorang et al. 2020). The gasifying agent is an essential element that affects the amount and quality of the products produced in these gasification reactions (Guan et al. 2016). The usage of various gasifying agents provides various reactions and gas compositions. The reactions listed below include both endothermic and exothermic reactions that result in heat absorption and emission. The enthalpy value of each reaction will be used to identify the type of reaction in which an exothermic reaction represents a negative value and a positive value indicating an endothermic reaction. The carbon reactions are Equation 2.1 to 2.3. Equation 2.1 shows the Boudouard reaction where the gasification of biochar occurs in the presence of CO_2 (Shahbaz et al. 2017) while Equations 2.2 and 2.3 represent steam formation, where H_2 is produced when biochar reacts with water, resulting in primary and secondary steam formation, respectively.

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

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

$$C + H_2O \leftrightarrow CO_2 + H_2 \qquad (+90\ kJ/mol) \qquad 2.3$$

Equation 2.4 represents the hydrogasification reaction in which methane (CH_4) gas is produced when biochar reacts with hydrogen and heat is released in the process, indicates that the process was exothermic (Ren et al. 2020).

$$C + 2H_2 \leftrightarrow CH_4 \qquad (-74.8\ kJ/mol) \qquad 2.4$$

The oxidation reactions that take place during biomass gasification are shown in Equations 2.5 to 2.9. Char, CO, CH_4 and H_2 are oxidised to produce their respective products.

$$C + 0.5O_2 \rightarrow CO \qquad (-111\ kJ/mol) \qquad 2.5$$

$$C + O_2 \rightarrow CO_2 \qquad (-394\ kJ/mol) \qquad 2.6$$

$$CO + 0.5O_2 \rightarrow CO_2 \qquad (-284\ kJ/mol) \qquad 2.7$$

$$CH_4 + 2O_2 \leftrightarrow CO_2 + H_2O \qquad (-803\ kJ/mol) \qquad 2.8$$

$$H_2 + 0.5O_2 \rightarrow H_2O \qquad (-242\ kJ/mol) \qquad 2.9$$

Equation 2.10 shows the water shift reaction where CO and H_2O react to form CO_2 and H_2 (Samimi, Marzoughi, and Rahimpour 2020). This reaction provides pure hydrogen that is essential in PG.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (-41.2\ kJ/mol) \qquad 2.10$$

Equations 2.11 to 2.13 are chemical reactions for methanization. The by-product of this reaction is CH_4 in the form of gaseous. The CH_4 produced is a portion of PG and is one of the components that allows it to combust.

$$CO + 2H_2 \rightarrow CH_4 + CO_2 \qquad (-247\ kJ/mol) \qquad 2.11$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad (-206\ kJ/mol) \qquad 2.12$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (-165\ kJ/mol) \qquad 2.13$$

Equations 2.14 and 2.15 are steam reactions in which both reactions primarily produce H_2. Steam reaction in gasification have the benefit of producing extra H_2 in comparison to air gasification alone, which produces low quality of PG.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad (+206\ kJ/mol) \qquad 2.14$$

$$CH_4 + 0.5O_2 \rightarrow CO + 2H_2 \qquad (-36\ kJ/mol) \qquad 2.15$$

2.3.2 Types of Biomass Gasifier

There are four types of biomass gasifier types that will be discussed in this section, which are:

i. Updraft gasifier
ii. Downdraft gasifier
iii. Cross draft gasifier
iv. Fluidized bed gasifier

2.3.2(a) Updraft Gasifier

(Ding et al. 2018) conducted an experiment to characterise biomass gasification of carbonized wood pellets and wood briquettes using an updraft fixed-bed gasifier. The updraft gasifier consisted of reaction zones (drying, pyrolysis, reduction and combustion) from top to bottom. Figure 2.4 shows the reaction zones in updraft gasifier. The carbonized pellets and briquettes were fed into the gasifier using a screw feeder. The syngas produced through the process of gasification was drawn out by the aid of a blower and transported to a purification system and lastly to a gas engine. The concentrations of CO and H_2 were kept almost constant in syngas for power generation following the system reached stable state. The LHV of the syngas produced was above 4 MJ/m^3 which is sufficient for combustion to occur.

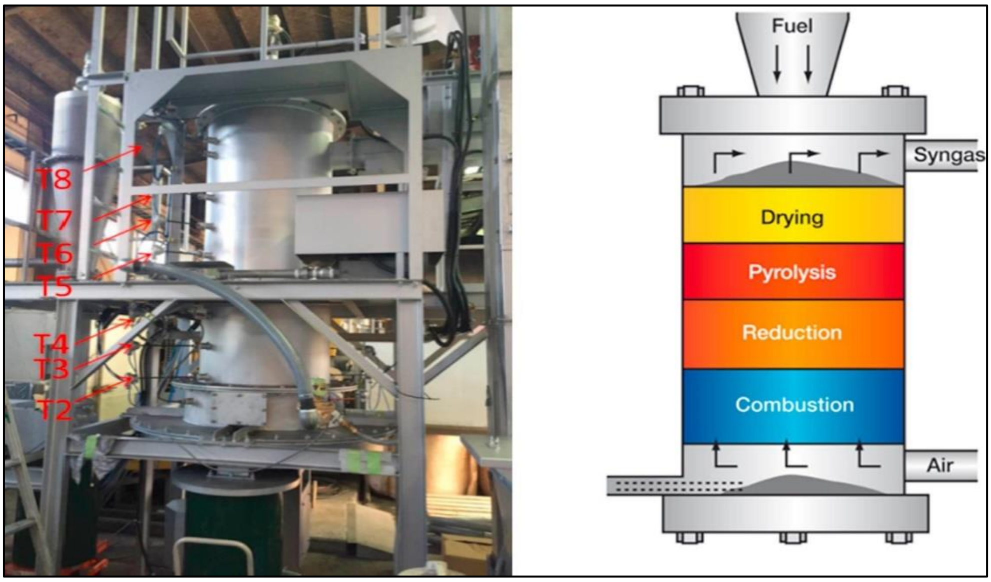

Figure 2.4: Updraft gasifier used in the research by (Ding et al. 2018)

(Cerone et al. 2020) conducted an experiment to identify and characterize syngas composition by using an updraft fixed-bed gasifier. Almond shells were used in this experiment as a biomass feedstock. The almond shells were fed into the gasifier using a feeding system that included screw feeders and a collecting chamber at the top of the gasifier. In this experiment, gasifying agent such as air and steam were used to analyse the syngas composition. The gas sample was obtained by sampling the gaseous stream at the output of the biodiesel scrubber and the syngas composition was analyse using gas chromatography. Figure 2.5 shows the updraft gasifier used in this research. The LHV of produced syngas achieved by using air as a gasifying agent is 6.20 MJ/Nm^3. The LHV of the syngas produced is 6.43 MJ/Nm^3 when mixture of air and steam was used as gasifying agent. However, the excessive tar content in updraft gasification is a main problem that affects power generation in motors or turbines by using syngas. In this research, the amount of tar has increased to 137 g/kg of dry almond shells for air gasification, and for air-steam gasification, tar produced is 163 g/kg of dry almond shells.

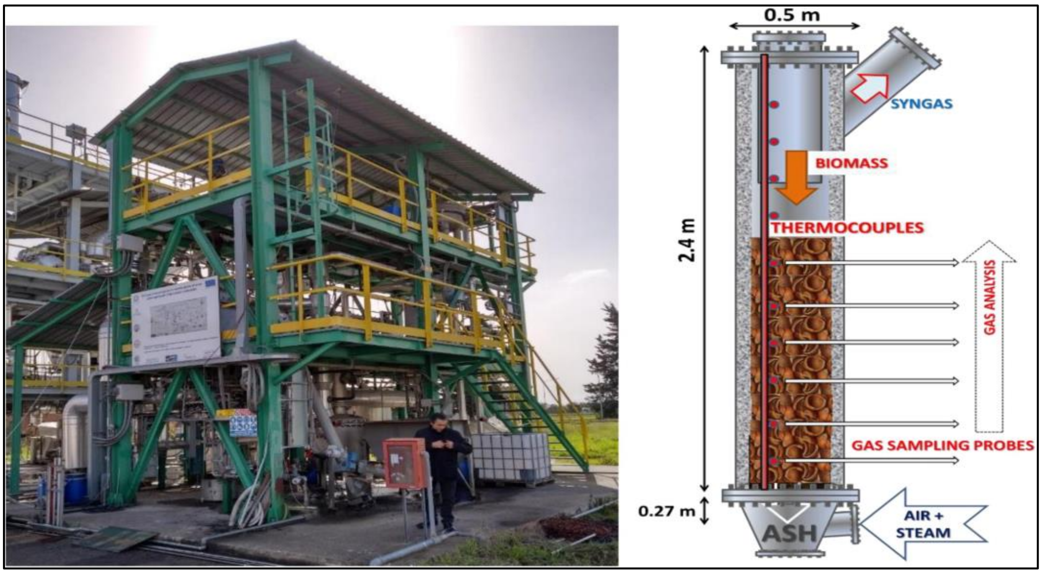

Figure 2.5: Updraft gasifier used in the research by (Cerone et al. 2020)

2.3.2(b) Downdraft Gasifier

(Sazali, Al-attab, and Zainal 2019) used a double walled throatless downdraft (DWTD) gasifier by using air fogging system to produce high quality of PG. Air blower was used to blow the PG generated from the gasifier. Figure 2.6 shows the schematic diagram of the overall gasification system.

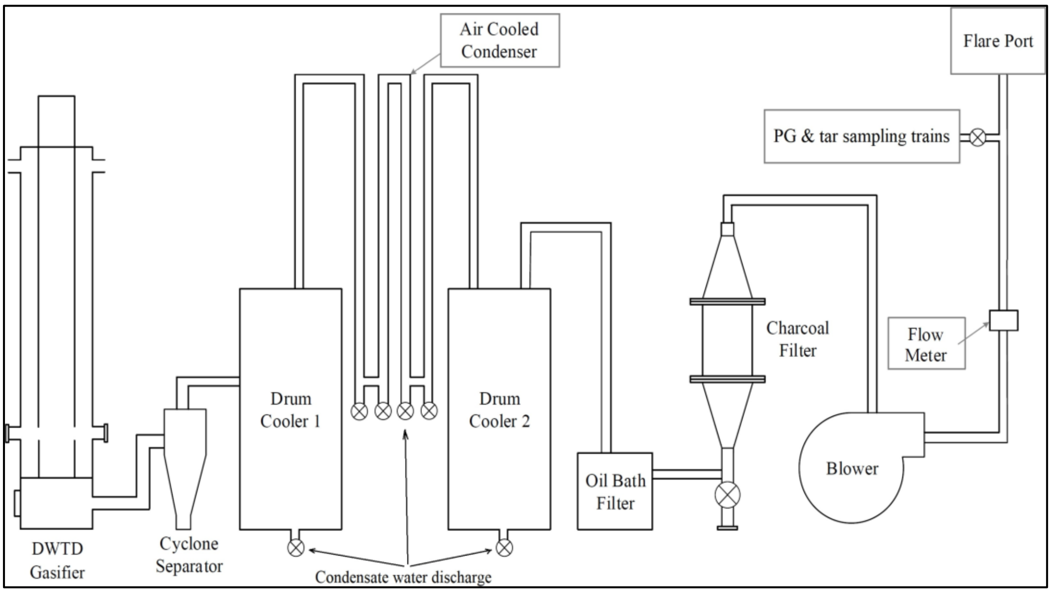

Figure 2.6: Schematic diagram of DWTD gasifier with air fogging unit (Sazali, Al-attab, and Zainal 2019)

The air fogging unit was connected to annulus of the gasifier to allow steam generation which will act as an extra oxidizer. The steam injection will increase the quality of PG and decrease the tar concentration. The drum coolers are act as a cooling system to condense the water vapour to improve the PG quality. During the cooling process, small quantities of tar and condensed water are removed. The high concentration of tar in PG is removed using the cleaning system. For the PG and tar sampling procedures, two sample trains were utilized to assure the removal of contaminations from sample. The PG was collected using Teflon sampling bags. For the air-gasification system, the H_2/CO ratio from the PG produced was 0.34, which was increased to 0.5 at S/B ratio of 0.25. The best gas quality was obtained when the S/B ratio was between 0.15 and 0.2, with an average LHV of 4.7 MJ/m^3. The LHV decreased drastically to even 4.19 when the S/B ratio increased to 0.3 primarily because of the significant increase in CO_2 concentrations. The usage of downdraft gasifier contributed to much lower tar contamination in this research.

(Pang et al. 2020) used downdraft gasifier for hydrogen production from steam gasification of corn straw. The PG produced by steam gasification can achieve more than 60% of H_2 concentration when compared with air steam and oxygen steam gasification. The direction of gas flow in the downdraft gasifier is from top to bottom which passes through the drying, pyrolysis, oxidation and reduction zone respectively. The system consisted of downdraft gasifier system, a steam generator, a gas clarifying system, a sample gas collection system, a gas composition analysis system, and a control system. The gasifier temperature measurement was carried out using six thermocouples from top to bottom. The gas composition was analysed using the gas chromatography method. The maximum LHV of PG from corn pellet gasification for the steam flow rate of 0.55 kg/h is 11.5 MJ/Nm^3 at the temperature of 700°C. For the steam flow rate of 0.75 kg/h, the maximum LHV of PG from the corn pellet gasification is 11.3 MJ/Nm^3 at 700°C.

2.3.2(c) Cross draft Gasifier

In the cross draft gasifier, the air is injected on one side of the reactor and PG is collected from the other side of the reactor as shown in Figure 2.7. The pyrolysis zone surrounds the reduction and combustion zones while drying zone forms the outer shell around all zones.(Ren et al. 2020) have mentioned in their research article the cross draft gasifier offers great benefit in terms of PG generation since it has high flexibility. The reactor size is not so large, which saves space and also takes a short time to start the reactor. The main challenge with this type of reactor is that the small size and high quantities of biomass material are difficult to treat. For rural household application, (Nwakaire and Ugwuishiwu 2015) has been conducted with a natural cross-section gasifier stove. The biomass used was rice husk briquette with moisture content of 8.5%. Figure 2.8 shows both 3D and sectional views of the cross-draft gasifier used in this experiment. As shown in the diagram, the system includes a pot stand on top of a gas burner that will serve as the stove. The system efficiency was 21.11 %, with a fuel consumption of 3.08 kg/hr.

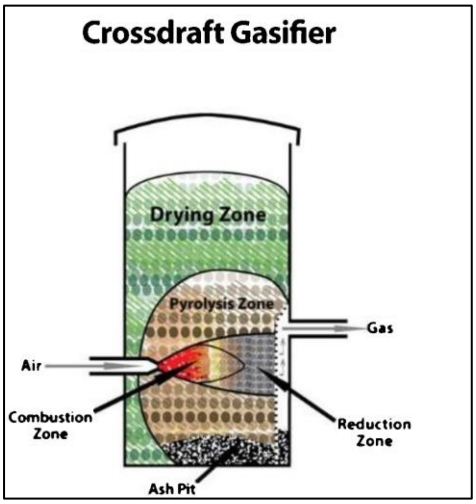

Figure 2.7: Cross draft gasifier (Hosseinpour Vardin and Najafi 2018)

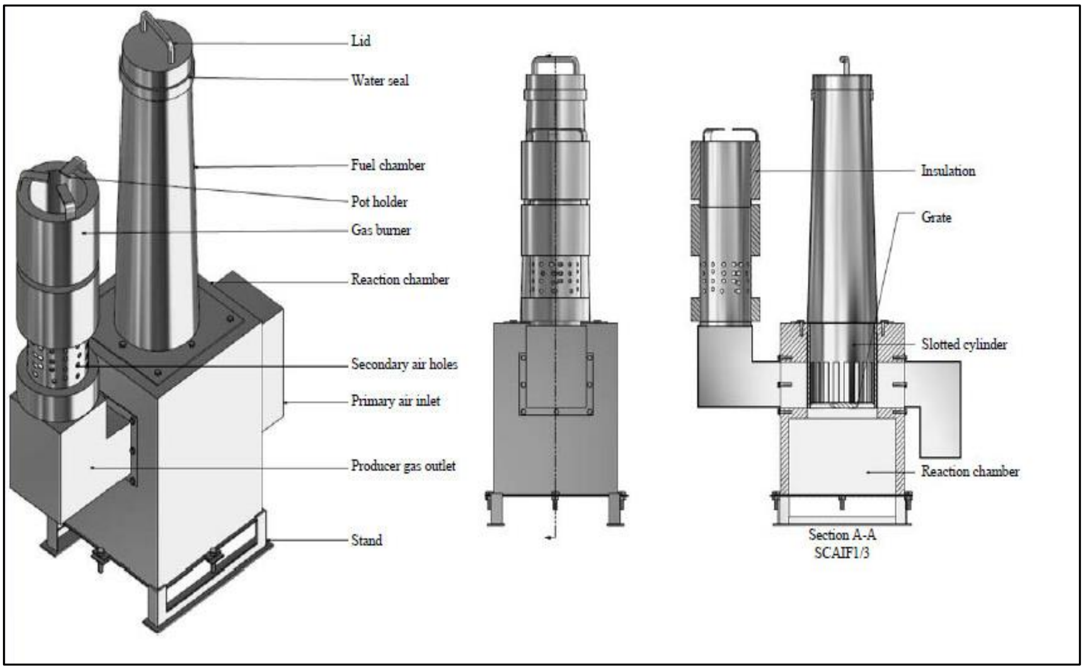

Figure 2.8: 3D view and sectional view of cross draft gasifier (Nwakaire and Ugwuishiwu 2015)

(Saravanakumar, Haridasan, and Reed 2010) conducted a research using cross draft gasifier with capacity of 50 m^3/hr. The cross draft gasifier was developed because it can produce PG with a low tar concentration. Mild steel sheet was used to fabricate the cross draft gasifier. Figure 2.9 shows the schematic of the cross draft long-stick wood gasifier used in this research.

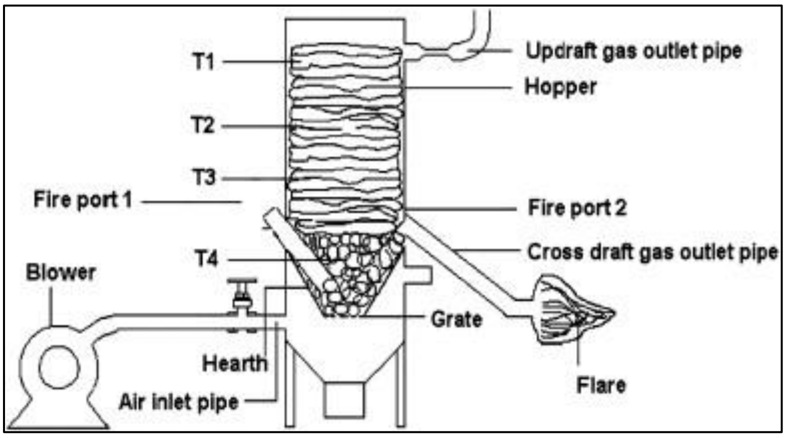

Figure 2.9: Schematic of cross draft gasifier(Saravanakumar, Haridasan, and Reed 2010)

The effect of temperature at different zones in the gasifier were discussed as well as the composition of PG with relation to distance from the bottom of the gasifier and time. This cross draft gasifier can be used for the production of heat from 8 – 10 kW for thermal cooking with the assist of 3W of blowers. It was found that the efficiency of the cross draft long stick wood gasifier is 79%.

2.3.2(d) Fluidized bed Gasifier

(Benedikt et al. 2018) conducted an experiment by utilised an advanced 100 kW dual fluidized bed gasifier for gasification process. Various types of biomass feedstock were tested in this research such as biogenic fuels, municipal solid waste fraction and lignite. The gasifying agent used in this research was steam. Various bed materials were tested for the gasification process which are limestone, quartz and olivine. Figure 2.10 shows the advanced design of the 100kW dual fluidized bed steam gasification pilot plant.

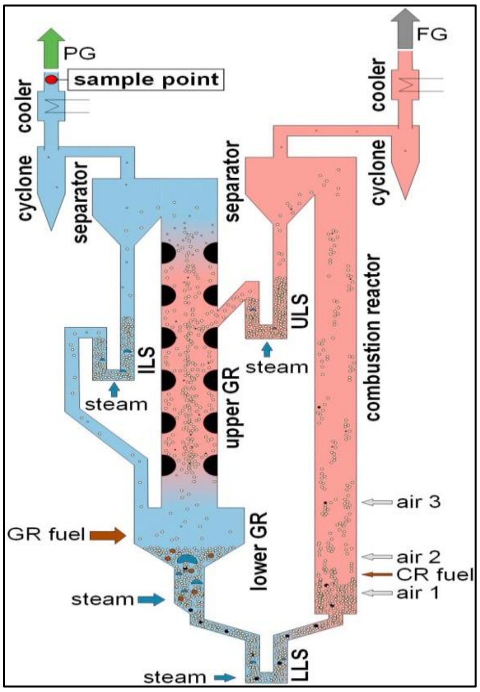

Figure 2.10: Design of the 100 kW dual fluidized bed steam gasification pilot plant (Benedikt et al. 2018)

A programmable logic controller is used to regulate the pilot plant. The programmable logic controller is used to continually measures and records data on all necessary flow rates, temperatures, pressure and the PG composition. In this research, the steam/fuel ratio and steam/carbon ratio was maintained within a reasonable range. Biogenic fuels and lignite produced the lowest tar concentration in PG, whereas waste-derived fuels produced slightly higher tar contents. (Benedikt et al. 2018) mentioned that the PG generation and LHV of the PG are influenced by the volatile matter of the fuel. As a result, PG with a LHV of around 11-12.5 MJ/Nm^3 was produced for biogenic fuels. The LHV of the PG of waste-derived fuels were around 14-16 MJ/Nm^3 and the gravimetric tar contents of the PG were high in a range of around 15-20 g/Nm^3. The researchers concluded that the higher the volatile matter of the fuel, the higher the lower heating value and PG generated.

(Karatas and Akgun 2018) conducted an experiment on gasification of walnut shell and pistachio shell in a bubbling fluidized bed gasifier by using steam and air as gasifying agent. The bed material used for the gasification process was silica sand. Figure 2.11 shows schematic diagram of experimental set-up for gasification. The experiment was conducted with using two different gasification agents which are steam and air. The air was provided to the reactor at ambient temperature by using an air compressor. The air temperature was maintained at 20°C and the equivalence ratio was varied for air gasification case. The steam was generated using a steam generator, which creates saturated steam. For steam gasification, the steam was injected at 230 °C and the steam-to-fuel ratio was varied. In steam gasification tests, the biomass feedstocks were gasified by changing the steam to fuel ratio between 1.11 and 0.41.

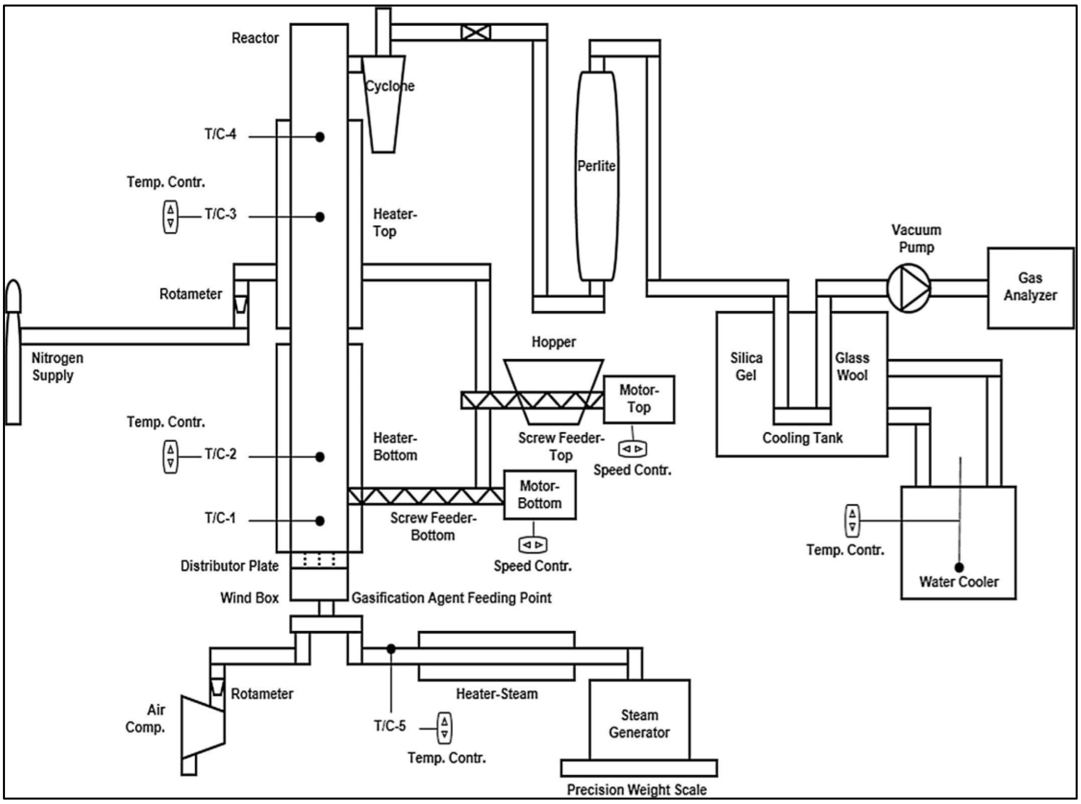

Figure 2.11: Schematic diagram of experimental set-up for gasification (Karatas and Akgun 2018)

A gas analyzer instrument was used to measure the gas composition in volume fractions and on a dry basis. The CO_2 and H_2 concentrations for walnut shell and pistachio shell decrease as the steam to fuel ratio decreases. The gasification agent has a crucial impact on the quality of PG. The utilisation of steam as gasifying agent has increased the production of CO, CH_4 and H_2. The LHV increases from 4 to 10 MJ/Nm^3 when the gasifying agent changed from air to steam. The researchers have mentioned that the bubbling fluidized bed offers excellent heat transmission characteristics and has a strong scale-up potential.

(Fremaux et al. 2015) have carried out a study on hydrogen-rich gas production via steam gasification of biomass in a research scale fluidized bed. Wood residues are used as biomass feedstock. The bed material used for the gasification process was silica sand which aided tar cracking process. The influence of steam/biomass ratio on PG composition for a reaction temperature of 900 °C was explored. The production of H_2 and CO_2 is more when the steam/biomass ratio is increased because of the water gas shift reaction. The maximum LHV of PG from wood residue gasification is 13.72

MJ/Nm^3 at 900°C in steam/biomass ratio of 1.0. It was also discovered that increasing the reactor temperature resulted in a huge reduction in tar concentration in PG.

2.4 Literature Summary

To summarize the literature review, biomass is a promising candidate for energy sources and gasification is among the most efficient methods to maximize energy. The chemical reactions that occur within the gasification process were shown as well. As for the gasifier types, fixed bed gasifiers (updraft, downdraft and cross draft) and fluidized bed gasifier were reviewed. Only a few papers could be found with steam gasification processes for downdraft gasifier. Downdraft gasifier has a lot of advantages such as having low tar concentration and having a higher carbon conversion rate. In all the literature reviewed, steam gasification was able to produce PG with better quality in the sense that it has high LHV. The main reason is the water-gas shift reaction that occurs in the gasification process.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This project is an experimental work to characterize the gasifier performance in terms of the gas quality at different steam/biomass(S/B) ratios. A small-scale self-sustained gasifier was fabricated for steam gasification. An electric steam boiler was used for steam production that will be used as gasifying agents in the experiment. The biomass fuel used for the gasifier is wood pellet. Figure 3.1 shows the flow chart of the methodology for the project conducted.

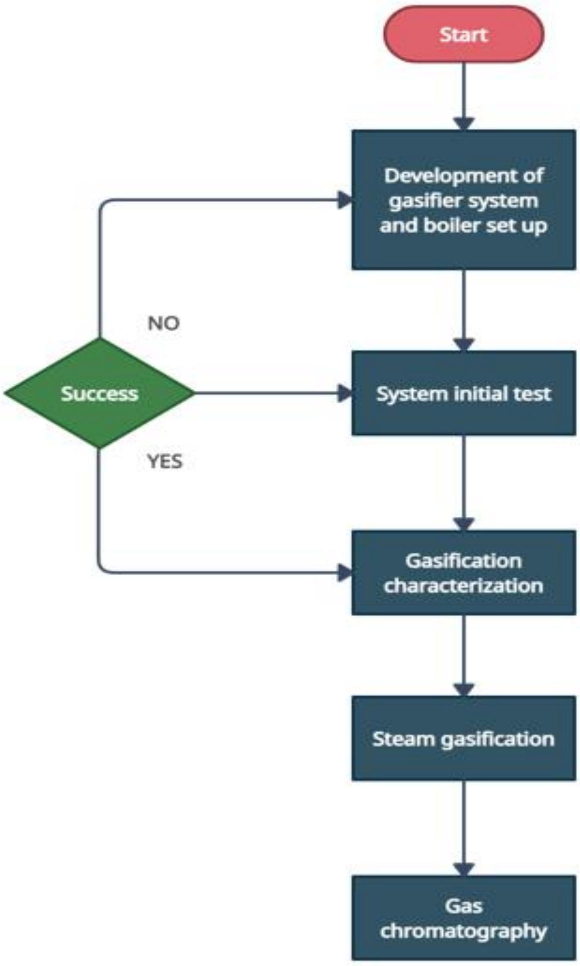

Figure 3.1: Methodology flow chart for the project

3.2 System setup

The system setup consists of the boiler setup includes the water flow system and the downdraft gasifier setup. The fabrication and modification done to the system will be discussed in this part as well. The schematic diagram of gasification setup was shown in Figure 3.2.

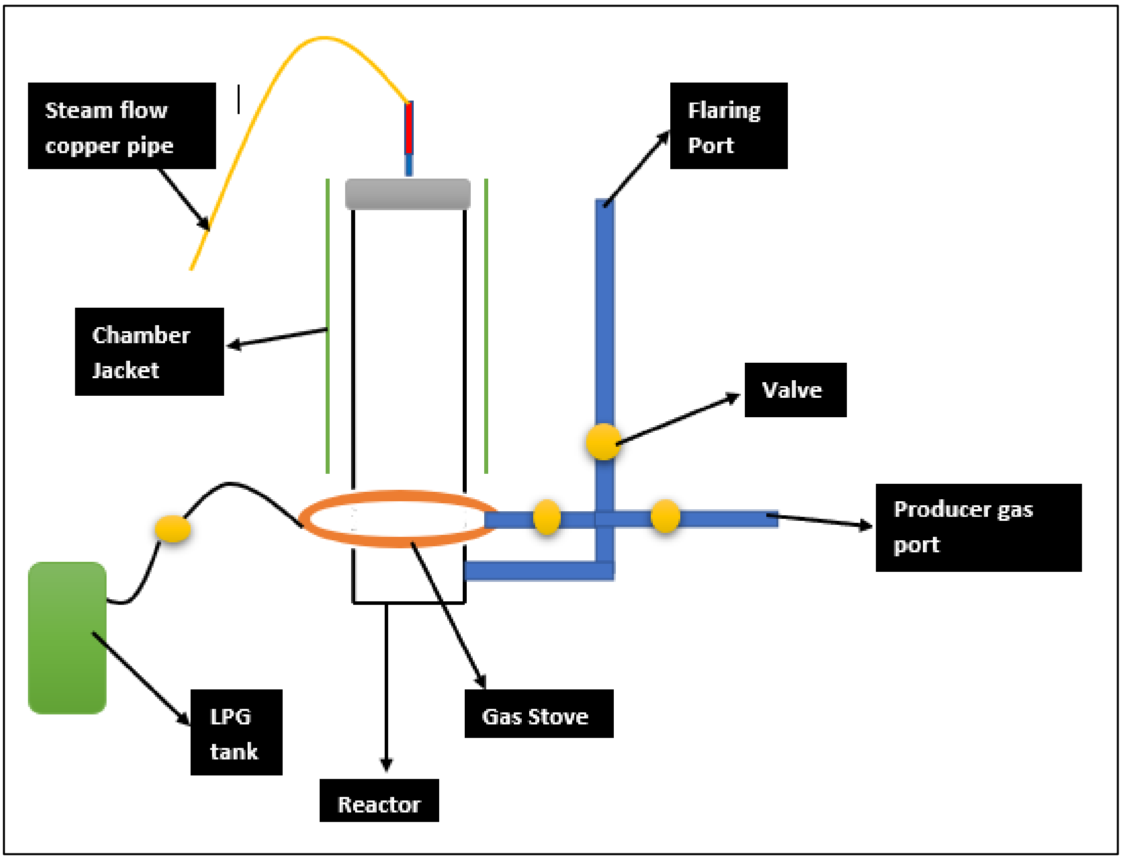

Figure 3.2: The schematic diagram of gasification setup

3.2.1 Boiler system

An electric steam boiler which is used for steam production was modified in Biomass Lab USM Engineering campus. The electric steam boiler was made by SIMONS BOILER CO and the type of model is SB 3S. Figure 3.3 shows an electric steam boiler used in this experiment.