PERFORMANCE COMPARISON OF STEAM AND AIR-STEAM GASIFICATION REACTOR

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PERFORMANCE COMPARISON OF STEAM AND AIR-STEAM GASIFICATION REACTOR

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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 ABBREVATIONS

BFBG	Bubbling Fluidized Bed Gasifier
CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide gas
CFBG	Circulating Fluidized Bed Gasifier
EFB	Empty Fruit Bunch
GHG	Greenhouse Gas
H_2	Hydrogen
HHV	High Heating value
LHV	Low Heating value
LPM	Litre per minute
LPG	Liquid petroleum gas
MF	Mesocarp fiber
N_2	Nitrogen
OPF	Oil Palm frond
O_2	Oxygen
PG	Producer gas
PKS	Palm kernel shells
S/B	Steam to biomass ratio
USM	Universiti Sains Malaysia

LIST OF SYMBOLS

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

ABSTRAK

Sumber tenaga boleh diperbaharui digunakan dengan lebih kerap akibat daripada peningkatan permintaan tenaga dan kebimbangan alam sekitar. Sumber tenaga lestari yang semakin meningkat ialah biojisim. Proses termokimia dan biologi adalah yang paling biasa untuk menukar biojisim kepada tenaga. Apabila agen pengegasan digunakan, bahan api pepejal ditukar kepada bahan api gas yang dikenali sebagai PG melalui proses termokimia yang dipanggil pengegasan. Pengeluaran hidrogen yang tinggi tidak dapat dicapai apabila udara digunakan sebagai agen pengegasan. Untuk menyelesaikan isu ini, agen pengegasan akan digunakan kerana wap boleh meningkatkan pengeluaran hidrogen. Pengegas biojisim stim lestari sendiri telah diubah suai dan direka untuk membolehkan bekalan stim yang betul dan sepenuhnya kepada tindak balas. Oleh itu, penggunaan wap sahaja dan wap yang digabungkan dengan udara sebagai agen pengegasan telah diterokai dalam penyelidikan ini. Stim dijana menggunakan dandang stim elektrik. Prestasi pengegasan dan proses pengegasan telah dicirikan berdasarkan pelbagai parameter seperti alur keluar pengegas dan suhu parut, kadar aliran wap, nisbah stim-ke-biojisim, nilai pemanasan dan komposisi gas pengeluar di bahagian atas. Kadar aliran wap yang digunakan adalah dalam julat 11.24 hingga 40 ml/min untuk pengegasan stim pelet kayu dan kadar aliran stim optimum digunakan untuk pengegasan wap bahan api biojisim yang berbeza dan pengegasan wap udara pelet kayu. Bagi pencirian pengegas pula, suhu tertinggi yang direkodkan pada jeriji ialah 545 ºC dan 510 ° C di alur keluar untuk pengegasan wap pelet kayu. Nisbah S/B optimum untuk menghasilkan kualiti dan komposisi gas yang dikehendaki didapati 1.9 mempunyai HHV tertinggi 15.1 MJ/Nm^3 dalam pengegasan stim pelet kayu. Dalam pengegasan wap bahan api biojisim yang berbeza, pelet kayu didapati menghasilkan kepekatan hidrogen dan metana tertinggi dan HHV diikuti oleh PKS. Bagi pengegasan wap udara, suhu tertinggi yang direkodkan pada jeriji ialah 975 ºC dan 905 ° C di alur keluar. Dalam kajian ini, nisbah S/B optimum untuk menghasilkan kualiti dan komposisi gas yang dikehendaki didapati ialah 1.7 pada kadar aliran udara 50 LPM dan kadar aliran wap optimum yang mempunyai HHV tertinggi iaitu 5.27 MJ/Nm^3.

ABSTRACT

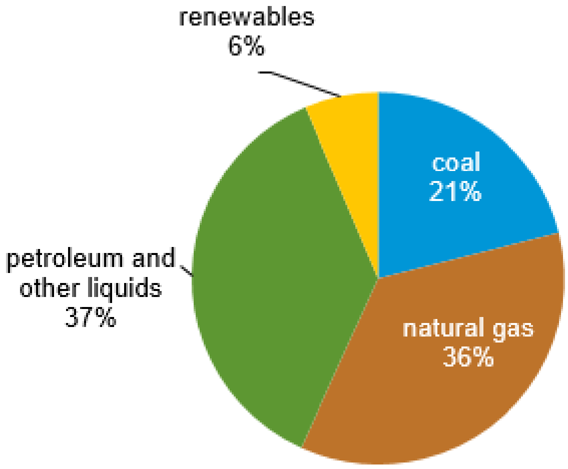
Renewable energy sources are being used more frequently as a result of rising energy demand and environmental concerns. A growing source of sustainable energy is biomass. Thermochemical and biological processes are the most common for turning biomass to energy. When a gasifying agent is used, the solid fuel is converted into the gaseous fuel known as PG by a thermochemical process called gasification. High hydrogen production cannot be attained when air is used as the gasifying agent. To solve this issue, a gasifying agent will be used because steam can improve hydrogen production. A self-sustained steam biomass gasifier was modified and fabricated to enable proper and fully supply of steam to the reactions. Thus, the use of steam alone and steam incorporated with air as gasification agents was explored in this research. Steam was generated using an electric steam boiler. The gasifier performance and gasification processes were characterized based on various parameters such as gasifier outlet and grate temperature, steam flow rate, steam-to-biomass ratio, heating values and producer gas composition at the top. The steam flow rates used are in the range of 11.24 to 40 ml/min for steam gasification of wood pellets and optimum steam flow rate is used for steam gasification of different biomass fuels and air-steam gasification of wood pellets. As for the gasifier characterization,the highest temperature recorded at the grate was 545 ºC and 510 ° C at the outlet for steam gasification of wood pellets. The optimum S/B ratio for producing the desired gas quality and compositions was found to be 1.9 having the highest HHV of 15.1 MJ/Nm^3 in steam gasification of wood pellets. In steam gasification of different biomass fuels, wood pellets were found to yield the highest hydrogen and methane concentrations and HHV followed by PKS. As for air-steam gasification, the highest temperature recorded at the grate was 975 ºC and 905 ° C at the outlet. In this study, the optimum S/B ratio for producing the desired gas quality and compositions was found to be 1.7 at air flow rate of 50 LPM and optimum steam flow rate having the highest HHV of 5.27 MJ/Nm^3.

CHAPTER 1

INTRODUCTION

1.1 Background

Global climate change is generally defined as a significant variation of average weather conditions, for example, conditions becoming warmer, wetter, or drier over a period. This change is caused by the high carbon dioxide emission throughout the atmosphere and is rapidly affecting the environment. Human activities are changing Earth's natural greenhouse effect by burning fossil fuels like coal and oil that puts more carbon dioxide into our atmosphere thus, increasing the greenhouse effect and leading to global warming. The usage of these fossil fuels that are categorized as non-renewable energy sources will deplete over time and hence, it has encouraged many to find renewable energy sources as an alternative to replace this depletion over time. Excessive use of fossil fuels is one of the main factors of increased carbon dioxide (CO_2) emissions. The encouraged usage of fossil fuels leads to increased emissions of greenhouse gasses which increases the temperature on Earth. The dependency on non-renewable energy sources for our country has increased over the years. Figure 1.1 shows the fossil fuel consumption by fuel type in Malaysia from the year 2019, the fossil fuel energy input in Malaysia is made up of 21.0 % coal, 36.0% natural gas and 37.0 % oil, and 6.0 % of renewable sources (“Country Analysis Executive Summary: Malaysia,” 2019.).



Source: BP 2020 Statistical Review of World Energy

Figure 1.1:Fossil fuel consumption in Malaysia in the year 2019 ("Country Analysis Executive Summary: Malaysia," 2019.).

In the year 2014, fossil fuel energy consumption in Malaysia was at 96.6 % which is a significant increase from 89.91 % in the year 1990 having an annual growth rate of 0.2 %. Figure 1.2 shows fossil fuel consumption in Malaysia from the year 1971 to 2022 (Macrotrends, 2022).

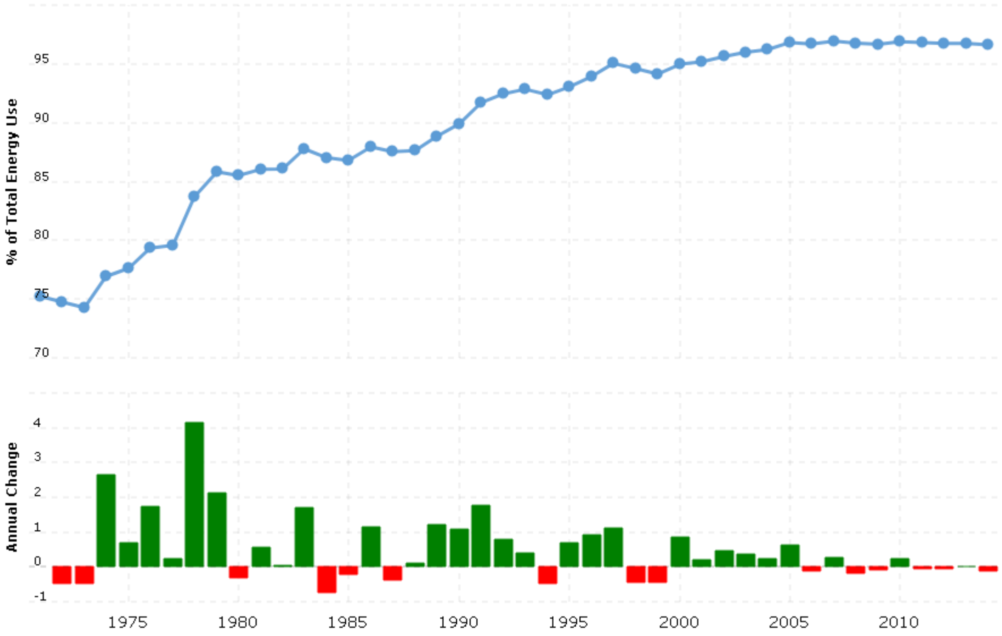


Figure 1.2: Malaysia fossil fuel consumption, 1971 to 2022 (Macrotrends, 2022).

From figure 1.2, the consumption of fossil fuels has risen over the years and proven that we have been very dependent on fossil fuels. The total CO_2 emissions in Malaysia has increased by 25.1 % over 10 years from 2009 to 2019 (Mohd Shahidan and Mohd Juraij 2021). Carbon dioxide has the greatest threat in direct global warming which is caused by emission of greenhouse gases influenced by fossil fuels. Figure 1.3 shows the cumulative carbon dioxide (CO_2) emissions produced from fossil fuels in Malaysia from the year 1970 to 2020 (Hannah Ritchie and Max Roser, 2020).

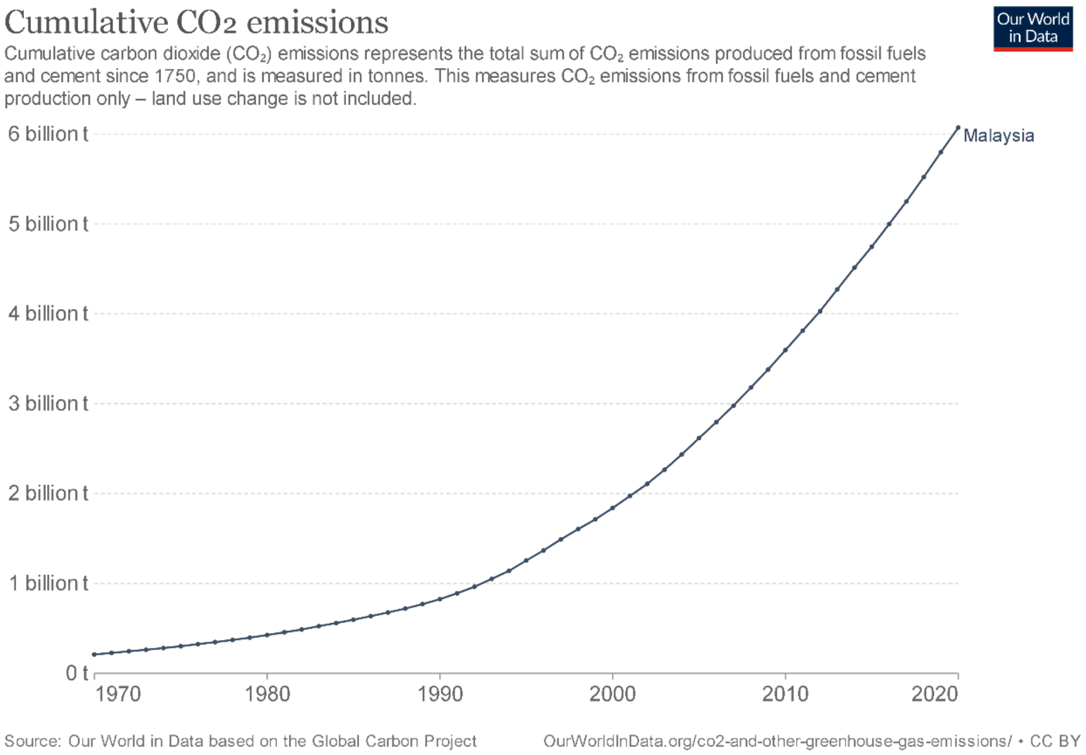


Figure 1.3: Cumulative carbon dioxide (CO2) emissions in Malaysia from 1970 to 2020 (Hannah Ritchie and Max Roser, 2020)

Although fossil fuels being the main source of power for the world and energy production, the process of extracting energy from this source produces a large amount of carbon dioxide (CO_2) emissions (Hannah Ritchie and Max Roser, 2020). The need to find an alternative to overcome this issue is extremely crucial and encouraging. If this problem persists, not only it will cause depletion of fossil fuels as non-renewable energy sources but also further worsen the agenda of global warming. Usage of renewable energy sources like biomass, hydropower, solar and geothermal that are environmentally friendly and are always available due to their regeneration must be encouraged. From this, hydrogen energy seems to be an important alternative energy source as it is not harmful to the environment and able to produce required amount of energy (Kaskun 2020). Production of rich hydrogen is essential as it is a source that can help the world minimize the levels of greenhouse gas emissions and has high energy content that can help in the sectors of power and energy prosper (Agyekum et al. 2022).

1.2 Biomass

Biomass is a growing potential of renewable energy that is developed from organic materials and a sustainable source of energy used to produce electricity and other forms of power mainly due to its abundance and reliability. Biomass is different from non-renewable sources like coal in many important ways like organic, inorganic, energy content and physical properties. Biomass generally has less carbon content and are also known as carbon neutral energy source (Chuah et al. 2006). Energy from biomass is called bioenergy which is a perspective source to replace fossil fuels.

Biomass can be combusted directly to generate heat and electrical energy. The major processes that compromise the utilization of biomass are thermo-chemical and bio-chemical conversion. By means of these processes, biomass can be converted into biofuels in forms of solids (e.g., charcoal), liquid (e.g., methanol) and gases (e.g., hydrogen) which are all used for power generation (Zhang, Xu, and Champagne 2010). The four fundamental thermo-chemical processes include combustion, pyrolysis, gasification, and liquefaction. Figure 1.4 shows the general pathways for biomass conversion into gaseous fuels. The highlighted routes indicate the conversion of biomass via thermos-chemical process means into gaseous fuels.

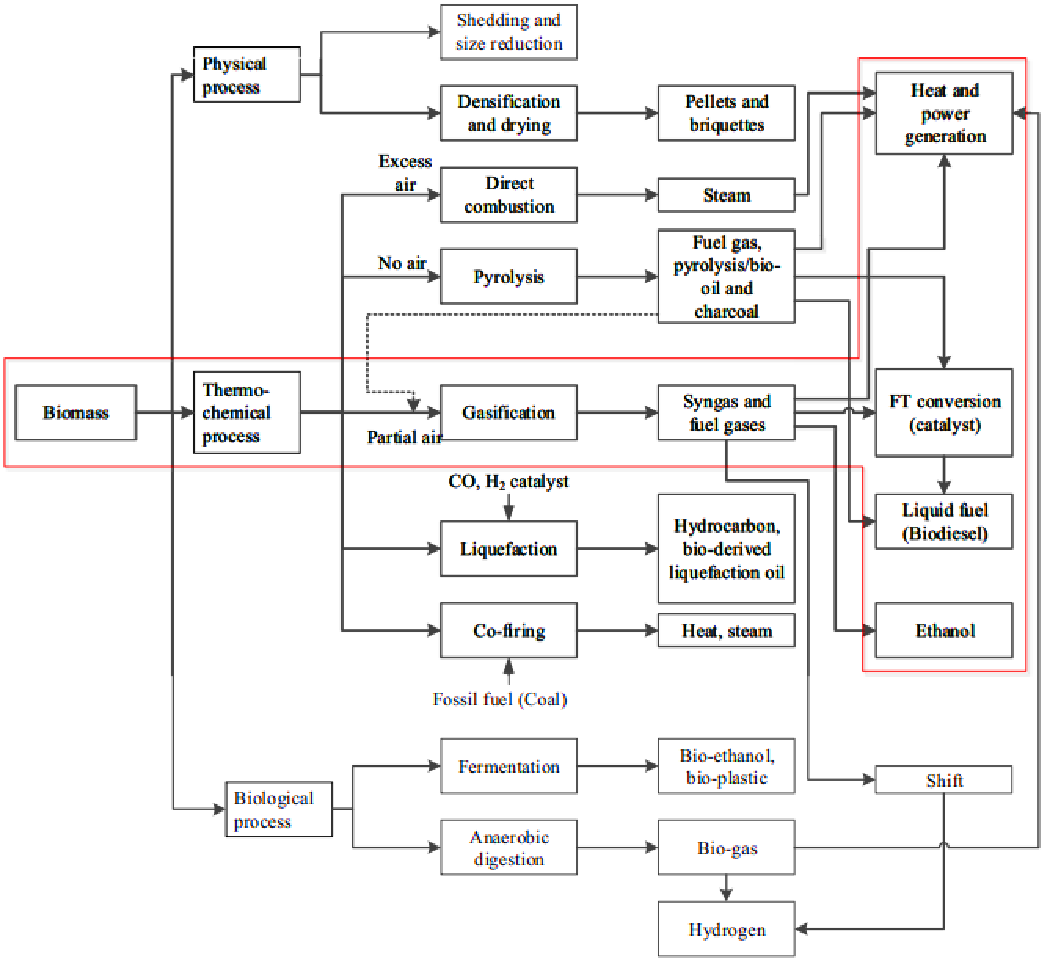


Figure 1.4: Pathways for biomass conversion into alternative fuels (Samiran et al. 2016)

Combustion is the most widely used process for biomass conversion. There are three main stages that occur during biomass combustion which are drying, pyrolysis and reduction. Combustion occurs in the presence of oxygen when heating (Bhaskar and Pandey 2015). Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen to convert biomass into biofuels in forms of solid, liquids and gases at elevated temperatures. Gasification is a process that converts biomass with partial oxidation into combustible gases like hydrogen, methane, etc. Liquefaction is a high pressure, low temperature process where biomass is broken down into small fractions in presence of water or a solvent (Zhang, Xu, and Champagne 2010).

1.2.1 Biomass Gasification

Biomass gasification is an environmentally friendly and coherent method to produce energy. Gasification process which involves solid biomass feedstock which are converted into gaseous fuels also known as producer gas or syngas for a range of applications like internal combustion engines and turbines (Rajvanshi, n.d.). Biomass gasification is the incomplete combustion of biomass resulting in production of combustible gases consisting of carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2). This mixture of gases is called producer gas. The producer gas also contains hydrocarbons with low molecular weight such as ethane and propane and hydrocarbons with high molecular weight such as tar that condense at temperatures above 250 and 300 °C. The process of gasification completes at elevated temperatures between 800-1300°C under a series of chemical reactions (Panwar, Kothari, and Tyagi 2012).

The gasification process occurs with the aid of a gasifier that is used as a reactor. This is where the conversion of biomass fuels fuel to gaseous fuels take place. The producer gas or syngas as the product of gasification process composes of gases like methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2) and carbon monoxide (CO). Utilizing biomass as feedstock is more promising than coal due to low sulphuric content and less reactive character.

The gasification process requires usage of gasifying agents such as air, steam, or carbon dioxide (CO_2) that provide oxygen for the formation of CO from solid carbon in the fuel (Jangsawang et al. 2007). The use of steam gasification has its advantages over the use of air gasification. Steam gasification is more sensible than air gasification when it comes to lesser formation of tar and good quality of producer gas composition. The gas produced by biomass gasification can be utilized to generate power in turbines and internal combustion engines.

1.3 Problem Statement

One of the most promising methods for producing sustainable energy is biomass gasification. Renewable energy sources have a number of environmental benefits. Among the topic, gasification of biomass, there are various investigations conducted on effects of the operating conditions of performance and efficiency of gasification in a downdraft gasifier. The production of good and high-quality producer gas is still challenging, and high tar content production is a major problem in biomass gasification which causes blockage and corruption which leads to corrosion of equipment such as turbines and engines. Air-gasification isn't ideal due to considerable nitrogen content contamination and low heating value gas produced by the gasification process that comes from air. The elimination of this dilution is by using steam-gasification which requires external heat source to occur and is fully endothermic when reacting with biomass. The issue with utilizing steam as a gasifying agent during steam gasification is the inability to control the scaled-up heat. Therefore, the main objective is to characterize the performance of the current small-scale gasifier equipped with self-heat supply, to overcome and analyse steam leakage at steam injection port and overcome high amount of nitrogen and oxygen in gas product. The experiments will be conducted on both air-steam and steam gasification operating modes and the gasifier performance is characterized in terms of gas composition and heating values at different steam/biomass (S/B) ratios. Producer gas will be analysed via a gas chromatograph machine.

1.4 Objectives

This project aims to:

1. To modify and redesign the existing small-scale gasifier reactor with external heat supply for gasification processes
2. To characterize the reactor in steam-gasification mode at different steam flow rates using wood pellets, steam gasification mode at optimum steam flow rate using various biomass feedstock (PKS, EFB and coconut shell charcoal briquettes) and in air-steam-gasification mode by using different air flow rates

and optimum steam flow rate with wood pellets to obtain gas compositions and heating values

3. To investigate the different biomass fuel (wood pellets, PKS, EFB and coconut shell charcoal briquettes) characteristics by conducting fuel analyses

.

1.5 Scope of Project

In this study, the biomass gasification system is experimentally studied, and the gasifier performance in terms of gas quality is characterised using steam-gasification and air-steam gasification systems. In order to characterise the performance of the gasifier in terms of gas quality (gas composition and heating values) at various steam/biomass (S/B) ratios, data from the experiment are gathered. The development of the steam injector port, which was formerly located at the bottom of the reactor but has now been moved to the top of the reactor to force the steam through biomass for efficacy at reaction zones, is the first stage in this investigation. When using an air-steam gasifier, the air injection port is positioned at the top of the reactor, allowing air to travel through the biomass. Gas is then collected from the reactor bottom. As for the biomass, the wood pellet is used in this experiment due to its high heating value. The experiment will be repeated using the palm kernel shell (PKS), empty fruit bunch (EFB) and coconut shell charcoal briquettes. The steam will be injected into the gasifier chamber at different steam flow rates. In air-steam gasification, biomass fuels used are only wood pellets and the optimum steam flow rate will be used. The thermocouple scanner will be used to measure and the record the temperature at the outlet exhaust gas. An external thermocouple will be used to measure the wall temperatures at top and bottom of the reactor. The producer gas sampling will be collected by using a gas sampling bag and sampling tubes through the cooling coil. The producer gas samples will be collected, and the gas composition will be analysed by using gas chromatograph machine. Elemental analysis and heating value analysis will be conducted for the biomass fuels used to analyse the fuels.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, we will discuss the importance and relativeness of biomass as a good renewable source as well as the several gasification processes and systems that incorporate biomass as fuels, steam and air-steam gasification processes, and diverse types of fuel analyses. The utilization of biomass has been proved to be a resourceful and practicable energy source as compared to fossil fuels by researchers conducting experiments worldwide in terms of energy output, availability, and reliability. Many works of literature that have been published show the statistics on the dependency of biomass as an energy source over time and the continuation of study and research on this topic is growing significantly proving to be that biomass is an absolute growing potential in this world. Biomass gasification consists of 4 main reactions in the thermos-chemical conversion route which are pyrolysis, oxidation, reduction, and tar reforming with their chemical reactions and gas compositions which will be discussed further and thoroughly. Biomass gasification for several types of gasifiers which includes fluidized bed, downdraft, updraft, and cross draft gasifiers will also be discussed thoroughly. The differences between the utilization of different gasifying agents and a variety of biomass feedstock will be discussed and compared with experiments conducted by researchers in terms of gas quality, syngas composition, and power generation along with the different methods of fuel analysis methods.

2.2 Biomass

The rapidly increasing population and industrialization in the world have made the need for energy increase worldwide. Based on the article by, (Tezer et al. 2022), it is stated that with the depletion of fossil fuels and the increase in environmental issues due to their immeasurable utilization, the move toward a clean, safe, and sustainable energy source is quickly taking place. Human activities are changing Earth's natural greenhouse effect by burning fossil fuels like coal and oil that puts more carbon dioxide into our atmosphere thus, increasing the greenhouse effect and leading to global warming. The usage of these fossil fuels that are categorized as non-renewable energy sources will deplete over time and hence, it has encouraged many to find renewable energy sources as an alternative to replace this depletion over time. In this research article, biomass has been proved to be the promising and most sustainable source of energy in terms of primary and total energy supply in the generation of fuels and power. The wide range of resources such as plants, forest wastes, animal waste, and industrial wastes as biomass sources shows that biomass as a renewable energy resource has its advantages in terms of availability, diversity, and sustainability (Tezer et al. 2022) mentioned that the contribution of biomass to primary energy was 55.6 EJ in 2017 which corresponds to 9.5 % of the total energy supply from all energy sources.

The utilization of biomass needs to be encouraged more to reduce the dependence on non-renewable energy sources such as fossil fuels as combustion of fossil fuels leads to greenhouse gas emissions (GHG) that cause global warming. From the research article by (AlNouss, McKay, and Al-Ansari 2020), it has been established that the reduction of carbon emissions is of the utmost significance and significance since it is anticipated that these emissions would rise from the present level of 160 megatons of carbon to a level of 640 megatons of carbon by the year 2100. Biomass as a growing potential and successor to being the main energy source has the capability to reduce carbon emissions by 20 % and at the same time generate sustainable power and fuels. It is also said that the consistent use of biomass as a renewable energy source would be difficult since typical biomass combustion processes have poor combustion efficiency. Nevertheless, there have been recent improvements and developments in biomass gasification processes such as the thermochemical conversion technique that converts biomass feedstock to high-energy combustible gases.

The term "biomass" refers to all combustible organic materials found in nature, most commonly those of animal and plant origin that are present in the environment. Straw, husk, cobs, bark, fruits, animal and plant wastes, grains, and agricultural wastes are all examples of common types of biomasses that are by products and residues of processing industries and farming (Pua et al. 2020). According to the authors of the study,(Mohammed et al. 2011), the thermochemical processes and the biological processes are the two basic mechanisms that are used in the process of turning biomass into energy. It is claimed that the thermochemical process is more successful than the biological process due to its faster reaction rate and higher capacity to convert. The thermochemical process converts solid biomass into gaseous fuel by making use of heat, while the biological conversion converts several kinds of biomass fuels into gaseous and liquid fuels. Figure 2.1 shows the possible biomass energy conversion routes.

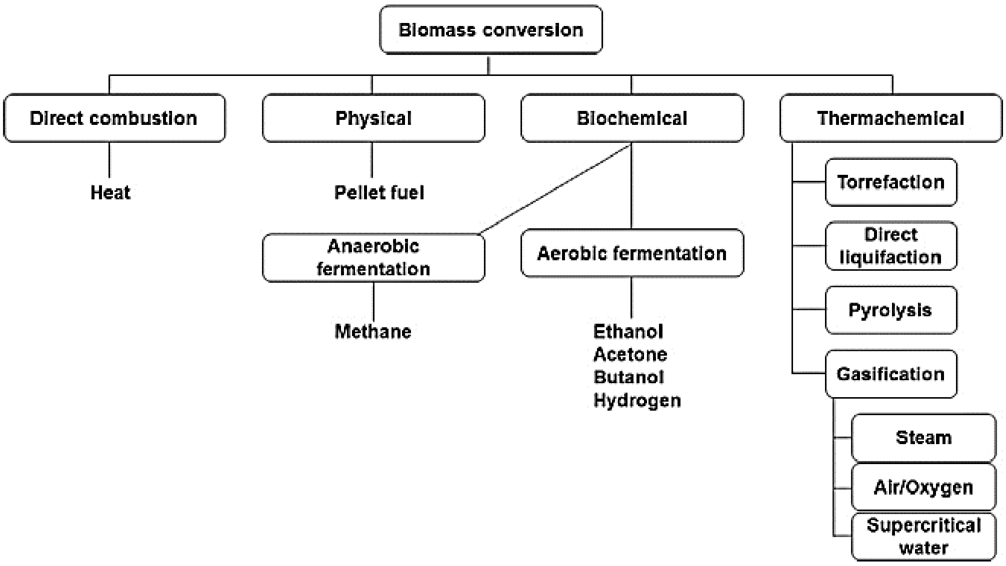


Figure 2.1: Biomass energy conversion routes (Guan et al. 2016)

Biomass is one of the most abundant renewable energy sources and is a growing potential as it contributes to a clean, renewable energy source that can significantly improve the environment and economy (Mohammed et al. 2011). The significance of hydrogen, H_2 as a clean energy source has been known as a clean energy carrier. The article by (Shuit et al. 2009), is stated that Malaysia is the second-largest producer and exporter of palm oil as Malaysia's palm oil industry leaves a large amount of biomass from its plantation activities as compared to other types of biomass feedstock. Palm oil is a valuable and important feedstock to the industry for edible oil production and the production of cosmetics, soap and more (Ng et al. 2012) From the study conducted by (Samiran et al. 2016), 4 types of Malaysian palm biomass are empty fruit bunch (EFB), palm kernel shell (PKS), mesocarp fiber (MF), and oil palm frond (OPF) are used. These palm-based biomasses have distinct and clear characteristics of their own. EFB has a high moisture content which requires excessive heat for the drying process and a high value of HHV of 32.1 MJ/kg for feasible syngas production. PKS and MF contain the most significant value of volatile matter content with low moisture and ash content and high heating values which makes them a good feedstock source for power generation. OPF has a relatively high HHV with a low moisture content making it a good biomass feedstock for the production of quality syngas. The high moisture content in oil palm biomass has a huge advantage for the thermochemical processes to make way for the generation of H_2 energy (Hossain, Jewaratnam, and Ganesan 2016). The research conducted by (Hossain, Jewaratnam, and Ganesan 2016), portrays the influence of different variables of thermochemical process tested that includes catalysts, temperature, and biomass to water mass ratio in identifying the hydrogen yield.

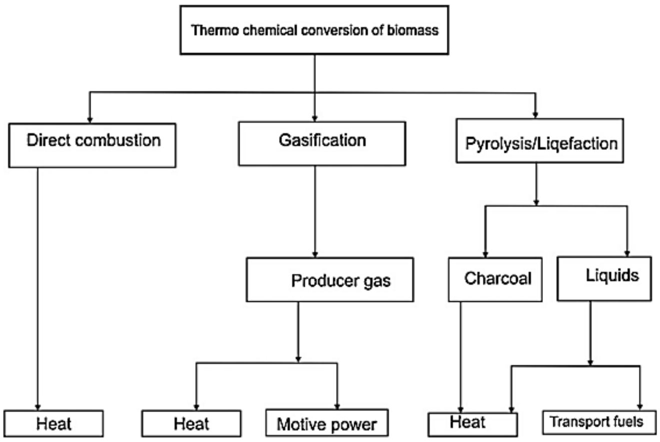


Figure 2.2: Thermochemical conversion route of biomass (Panwar, Kothari, and Tyagi 2012)

2.3 Biomass Gasification

Biomass gasification is the incomplete combustion or partial oxidation of biomass resulting in the production of combustible gases or gaseous fuels consisting of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2) through solid fuels. This mixture of gases is called producer gas, PG, or syngas (Ram et al. 2019). The producer gas or PG also contains hydrocarbons with low molecular weight such as ethane and propane and hydrocarbons with high molecular weight such as tar that condenses at temperatures above 250 and 300 °C. Producer gas can be used to run internal combustion engines, both compression, and spark-ignition engines, and can be used as a substitute for furnace oil in direct heat applications or in direct heat applications (Rajvanshi, 2014.). Over the years, biomass gasification has been developed to utilize wastes and to obtain decent quality producer gas. These gases can additionally be produced from biomass through biochemical routes (Sikarwar et al. 2016). However, this process requires a high amount of energy due to the endothermic behaviour of the reaction. The energy consumption during the gasification process is a major problem for the thermal efficiency and on the design of the gasifier (Ahmad et al. 2016).

When compared to the process of direct combustion, the thermochemical process, which is the simplest process, is said to have a high thermal efficiency due to its faster reaction rate and higher capacity to convert. Major thermochemical conversion routes can be classified into two routes which are direct combustion to supply heat and liquid fuel to generate process heat for electricity and power generation (Panwar, Kothari, and Tyagi 2012). Gasification process is a promising procedure to produce quality syngas where higher heating value fuels can be generated (Samiran et al. 2016). Gasification of biomass is also performed with the usage of different gasifying agents such as oxygen, air, steam or carbon dioxide, CO_2 and the mixtures which can result in the changes of the producer gas compositions (Pio et al. 2022). Figures 2.3 and 2.4 represent the growing number of publications on biomass gasification and the total capacity of main applications of biomass gasification over the years. Modern use of biomass has mainly focused on gasification on an adequate scale and over the years, 1.4 GWth of electricity and heat production capacity was installed and has successfully been utilized in the industry (Kirkels and Verbong 2011). This shows that the need for biomass under biomass gasification methods is desperately needed as they have higher efficiencies in power production and a more controlled heating. The rise in numbers is attributable to the advancements in technology that have taken place over the course of the years, which have played a role in the growth of research for the gasification of biomass. As a direct consequence of this, there have been more journal papers written about this technology throughout the course of the years. It is because of a desire to produce a renewable source of energy as well as an appropriate technology or system for maximizing the efficiency with which energy is used (AlNouss, McKay, and Al-Ansari 2020).

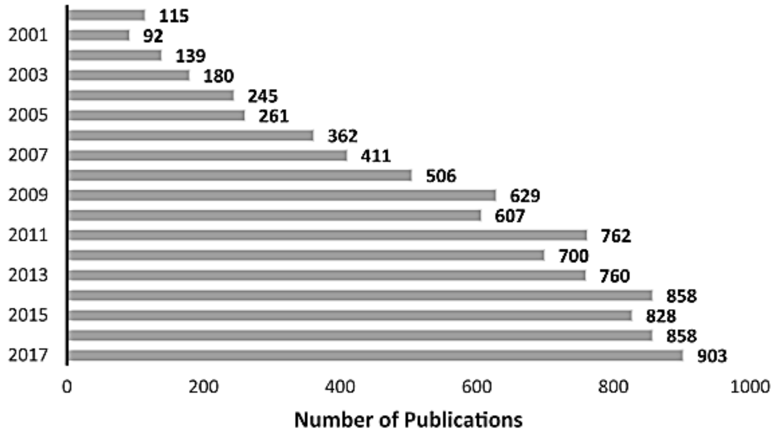


Figure 2.3: Number of publications on biomass gasification (AlNouss, McKay, and Al-Ansari 2020)

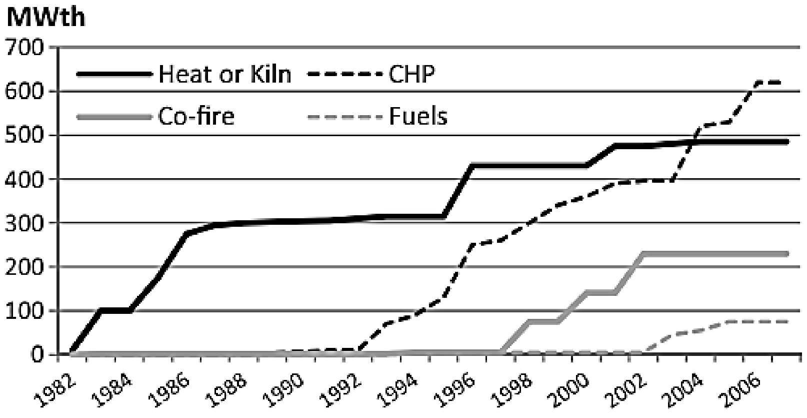


Figure 2.4: Acquired capacity of main applications of biomass gasification (Kirkels and Verbong 2011)

Based on the research by (Akhilesh Kumar, Randa, and Professor 2014), biomass gasification has sparked the most interest among thermochemical conversion processes, owing to its better efficiency and effectiveness than combustion and pyrolysis as it produces producer gas, PG that can be utilized to generate power and energy. Upstream processing, gasification, and downstream processing are the three primary processes in the gasification process (Ajay Kumar, Jones, and Hanna 2009). Drying, pyrolysis, combustion, and reduction are all critical phases in the gasification process (Tezer et al. 2022).

Figure 2.5 illustrates the paths of the biomass gasification process:

i. Drying and Heating

Endothermic evaporation of compounds with low boiling points occurs at a relatively low temperature of around 100 ° C during the drying and heating step, reducing the overall moisture content in the biomass.

ii. Pyrolysis

The thermochemical breakdown of biomass into volatile forms such as CO, CO_2, tars, light hydrocarbons, and pyrolysis liquid in an oxygen-free environment at temperatures ranging from 125 to 500 °C is referred to as the pyrolysis stage. During this process, hemicellulose, cellulose, and lignin in biomass are converted into char and volatile gases with varying molecular weights. After cooling to room temperature, some volatiles combine to form tar, a black viscous liquid containing hydrocarbons.

iii. Oxidation/Combustion

Combustion, or oxidation, is an exothermic process in which a gasification agent is fed into the system to react with the products acquired after the pyrolysis process, generating the heat required in the endothermic process. This process happens in temperature ranges of 700 ° C and above.

iv. Reduction

Char combines with hot gases entering from the upper zones in the reduction phase, also known as the gasification zone, to produce syngas or producer gas. This phase develops at temperatures higher than 800 ° C.

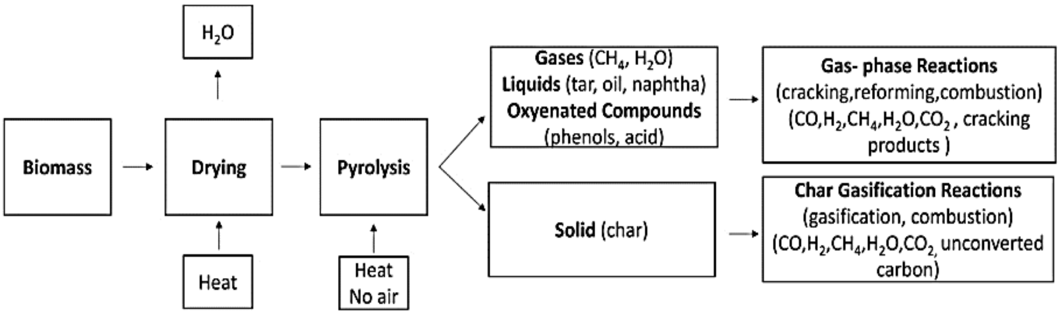


Figure 2.5: Paths of biomass gasification (Tezer et al. 2022)

The production of good and high-quality producer gas is still challenging, and high tar content production is a major problem in biomass gasification which causes blockage and corruption which leads to corrosion of equipment such as turbines and engines. The major drawback of air-gasification is air although cheap, it is not perfect because of high nitrogen content and contamination which can disrupt the quality and efficiency of the producer gas and product gas from air-gasification produce a low heating value, LHV gas obtained. The elimination of this dilution is by using Steam-gasification which requires external heat source to occur and is fully endothermic when reacting with biomass. The issue with utilizing steam as a gasifying agent during steam gasification is the inability to control the scaled-up heat. In biomass gasification, the presence of tar in output gas is a major problem to deal with. The tar can condense at decreased temperature at high concentration levels which results in blockage in process equipment's like engines and turbines (Rakesh N and Dasappa 2018). Hence tar disposal is also a necessary and critical approach during biomass gasification (Kumar Pattar et al., 2017.).

(Lv et al. 2007), conducted an experiment to determine hydrogen-rich gas production from biomass air and oxygen/steam gasification in a downdraft gasifier. A self-heated downdraft gasifier is used as a reactor and char is used as the catalyst to study the characteristics of hydrogen forming from biomass gasification. Air and oxygen/steam are used as the gasifying agents in this experiment. Pine wood blocks are utilized as the main biomass feedstock in this experiment. The reactor is labelled with 5 different points to indicate the temperature differences at each point during the procedure. The results are discussed and interpreted based on the temperature distribution in the gasifier, effect of feeding rate on hydrogen yield and hydrogen flow rate, effect of equivalence ratio, ER on hydrogen yield and flow rate, and the gas compositions in air and oxygen/steam gasification. From the results obtained, the maximum lower heating values, LHV of gas reaches 11.11 MJ/ Nm^3 for biomass oxygen/steam gasification and values of LHV obtained are higher compared to LHV obtained from air gasification. The maximum LHV of gas reaches 5.44 MJ/Nm^3 for biomass air gasification. The content of hydrogen yield obtained was 63.27-72.56 % for oxygen/steam gasification and 52.19-63.31 % for air gasification. The producer gas composition by steam-gasification was shown that can yield more than 60% of hydrogen (H_2) concentration as compared to air-gasification. The temperature distribution of air gasification showed much higher values as compared to oxygen/steam gasification. The tar content yielded in oxygen/steam gasification is comparatively much lower than that yielded in air gasification of biomass. The findings of the experiments and comparisons show that biomass oxygen/steam gasification in a downdraft gasifier is a viable, low-energy hydrogen-rich gas generation techniques as compared to air gasification.

Biomass gasification system have been developed worldwide by researchers throughout the world. The system is still being researched and investigated in various methods to improvise and enhance the gasification process of biomass to produce sustainable energy source. However, the specific findings regarding air gasification and steam/air gasification are not a vastly discovered topic and is still an ongoing and widely researched topic around the world among researchers.

2.3.1 Biomass Gasification Reactions

The biomass gasification process is made up of a sequence of exothermic and endothermic processes (Islam 2020). Gasification process in general includes 4 primary steps that is heating or drying, decomposition or pyrolysis, oxidation or partial combustion and reduction or gasification. During the gasification process, unwanted by-products like tars, ash and other impurities will be produced. Tar consists of complex mixtures of hydrocarbon materials which is necessary to be removed or further processed to prevent them from condensing at the downstream of equipment's which can cause serious issues like fouling of engines and deactivation of catalysts because of its polymerization and condensation characteristics. The early thermo-chemical breakdown of biomass, which creates tar, char residues, and volatiles, is followed by the secondary stage of reactions, which involves volatiles. The last stage involves heterogeneous interactions between leftover carbonaceous residues and producer gases, as well as homogeneous reactions between gases in terms of CO, CO_2, H_2, H_2O, and hydrocarbons (Gai and Dong 2012). The syngas produced is useful in important industrial applications like running internal combustion engines, generating electrical power, and producing liquid hydrocarbon by the Fisher-Tropsch method (Islam 2020).

The product distribution and efficiency during gasification process deviates significantly because of the occurrence some chemical reactions which relies mainly on gasifying agents, operating conditions like temperature and pressure, type of biomass source, composition and particle size and type of gasifiers used (Quiroga et al. 2022). The main reactions that occur during biomass gasification is summarized in table 1 showed below. Both endothermic and exothermic processes that result in heat absorption and emission are mentioned below. Each reaction's enthalpy value will be used to determine the kind of reaction, with a negative value suggesting an exothermic reaction and a positive value for an endothermic reaction.

Table 1.1: Gasification main reactions and their specific enthalpies

Gasification main reactions	ΔH (kJ/mol)	Eq.
$C + CO_2 \leftrightarrow 2CO$	(+172 kJ/mol)	2.1
$C + H_2O \leftrightarrow CO + H_2$	(+131.5 kJ/mol)	2.2
$C + H_2O \leftrightarrow CO_2 + H_2$	(+90 kJ/mol)	2.3
$C + 2H_2 \leftrightarrow CH_4$	(-74.8 kJ/mol)	2.4
$C + 0.5O_2 \rightarrow CO$	(-111 kJ/mol)	2.5
$C + O_2 \rightarrow CO_2$	(-394 kJ/mol)	2.6
$CO + 0.5O_2 \rightarrow CO_2$	(-284 kJ/mol)	2.7
$CH_4 + 2O_2 \leftrightarrow CO_2 + H_2$	(-803 kJ/mol)	2.8
$H_2 + 0.5O_2 \rightarrow H_2O$	(-242 kJ/mol)	2.9
$CO + H_2O \leftrightarrow CO_2 + H_2$	(-41.2 kJ/mol)	2.10
$CO + 2H_2 \rightarrow CH_4 + CO_2$	(-247 kJ/mol)	2.11
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	(-206 kJ/mol)	2.12
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	(-165 kJ/mol)	2.13
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	(+206 kJ/mol)	2.14
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	(-36 kJ/mol)	2.15

From the research article by (Situmorang et al. 2020b), equations 2.1 to 2.3 represents the carbon equations. Equation 2.1 indicates the Boudard reaction when gasification of char occurs in the presence of CO_2 to produce carbon monoxide, CO. Equation 2.2 is the primary steam reforming meanwhile equation 2.3 is the secondary steam reforming. and this is when steam is created, when biochar combines with water, resulting in primary and secondary steam formation, respectively. Equation 2.4 represents the methanation reaction which occurs in the reduction zone when the biochar reacts with hydrogen and heat is released during this time indicating an exothermic process. Equations 2.5 to 2.9 resemble the oxidation processes that take place during biomass gasification. Equation 2.5 is the partial oxidation of char that produces carbon monoxide, CO, and heat. Equation 2.6 is the total oxidation of char which provides carbon dioxide and more heat released. The amount of heat discharged during total oxidation is three times more than during partial oxidation (Susastriawan, Saptoadi, and Purnomo 2017). The oxidation zone consists of two reactions that occurs is the water gas-shift reaction and methanation reaction. The reduction zone consists of 4 main reactions that occur which are the Boudard reaction, water-gas reaction, water-gas shift reaction and methane reaction. The water-gas shift reaction, in which CO and H_2O combine to generate CO_2 and H_2, is depicted in equation 2.10. This process produces pure hydrogen, which is required in the production of PG (Guan et al. 2016). Equations 2.11 to 2.13 are the methanization reactions. Equation 2.11 is the dry reforming of methane and equation 2.12 is the steam-methane reforming (Islam 2020). Equation 2.14 and 2.15 are the steam reforming reactions to produce H_2 (Franco et al. 2003).

The use of steam as the gasifying agent in steam gasification process promotes H_2 and CO production through the primary and secondary water-gas, water-gas shift, and steam-methane reforming reactions. The use of air, oxygen, or pyrolysis conditions that is without the use of gasifying agents, mainly promotes the formation of CH_4 through the methanation reaction and CO formation through the Boudard reaction, partial oxidation of methane and dry reforming of methane reactions. The quality of syngas is influenced by the type of gasifying agent used. Compared to air gasification, steam gasification has a number of advantages. In terms of reduced tar generation and better syngas composition, steam gasification is more practical on a small and big scale than air gasification (Shahbaz et al. 2017).

2.3.2 Biomass Gasifiers

Gasifiers are the reactors where gasification reactions occur. Based on the reactions, a typical gasifier can be divided into four process zones which are the drying zone where water present in the biomass is evaporated, the pyrolysis zone where biomass is pyrolyzed into medium-energy calorific volatile gases, liquid and char, the combustion/oxidation zone where combustion takes place with limited amounts of oxygen supplied and lastly the reduction zone where H_2 and CO are produced (Zhang, Xu, and Champagne 2010). Various gasifiers have been developed to accommodate the gasification processes and the diverse types of fuels. The three types of biomass gasifiers are the fixed bed gasifier which includes the updraft, downdraft and cross draft gasifier, the fluidized bed gasifier which includes the circulating fluidized bed gasifier and bubbling bed gasifier and the entrained flow gasifier which are commonly applied. Each of these gasifying systems has relative advantages and disadvantages in terms of fuel type, application, and operation, providing possible technical and economic advantages under particular operating situations. The performance of a gasifier is determined by its operating state, stability, gas quality, and pressure losses in the system (Samiran et al. 2016). The types of biomass gasifiers which will be discussed are as follows:

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

Fixed bed gasifier consists of updraft, downdraft, and cross draft gasifier. In a fixed bed gasifier, a base of solid fuel particles is present which the gasifying products and gases either move up also known as updraft, move down known as downdraft or are presented on one side of the reactor and are released on the other side on the same reclining parallel level also known as cross draft. A fixed bed gasifier is the most direct type of gasifier typically compromising of a cylindrical space for feedstock and gasifying products with a fuel feeding unit, and ash removal unit and a gas exit. The fuel bed moves slowly down along the reactor as the gasification process takes place in a fixed bed gasifier. Fixed-bed gasifiers are easy to build and commonly run with high carbon conversion, low gas velocity, and low ash carry-over in most cases (Puig Arnavat, Bruno, and Coronas 2010).

2.3.2 (i) Updraft Gasifier

In updraft gasifiers, air is brought in at the bottom of the reactor and biomass is at the top of the reactor. This reactor requires an opposing flow of the biomass feedstock and gasifying agents like steam, air, or oxygen. The biomass that is fed from the top, moves into the drying zone following the pyrolysis zone where char is produced. At the gasification zone, char is moved to the bottom of the gasifier to undergo combustion with gasifying agents in the oxidation zone to produce end products, CO_2, and H_2O. The upstream of hot gas of gaseous pyrolyzed results is moved upwards to react with the feedstock from the upper area of the bed where H_2 and CO are produced and cooled. These gases are moved up further to pyrolyze the dry biomass moving downstream as they leave the reactor at reduced temperatures (Samiran et al. 2016).

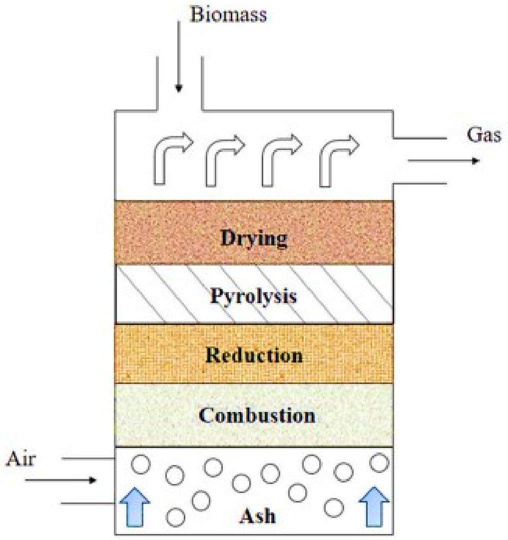


Figure 2.6: Schematic diagram of an updraft gasifier (Situmorang et al. 2020a)

(Chen et al. 2012) conducted an experiment on gasification of mesquite and juniper wood samples using an updraft fixed bed gasifier. The biomass fuels were prepared and underwent proximate and ultimate analyses to determine the composition of moisture, fixed carbon, volatile matter, ash, and heating values and to determine the elemental mass-based compositions that include C, H, N, O, and S. The particle sizes were fixed to 2-4 mm and 4-6 mm for both fuels. The grate is preheated, and thermocouples were placed along the vertical steep of the gasifier to record the temperatures. The highest temperature during the combustion process were recorded above 1000 ° C. It was found that high moisture content lowered the temperature peak and CO and H_2 mole percentage, but larger particle size resulted in increased temperature peak which produced increment in CO. The equivalence ratio, ER when increased was discovered to have decreased the CO and H_2 mole percentage but increased the CO_2 and N_2 mole percentage. The HHV for juniper ranged from 3500 kJ/Nm^3 to 3900 kJ/Nm^3 meanwhile for mesquite was 2400 kJ/Nm^3 to 3500 kJ/Nm^3. Juniper was found to have better gas quality due to lower nitrogen content and higher HHV.

(Cerone et al. 2020) carried an experiment to characterize the syngas composition in an updraft fixed-bed gasifier. Almond shells were used in this experiment as the biomass feedstock. Ultimate analysis of the biomass was conducted. Biomass was loaded in at 4-6 kg every 12 minutes in the feeding system at the top of the gasifier. Air and steam were used as the gasifying agents to analyze the syngas composition. The gas sample was taken from the gaseous stream at the biodiesel scrubber's output, and the syngas composition was determined using gas chromatography. The LHV of syngas generated with air as the gasifying agent is 6.20 MJ/Nm^3. When a combination of air and steam was utilized as the gasifying agent, the LHV of the syngas generated was 6.43 MJ/Nm^3. It was also found that tar production is higher when air and steam combined is used as gasifying agents (163 g/kg) as compared to the usage of air as the gasifying agent (137 g/kg). Tar contamination in the syngas or producer gas in an updraft gasifier is a major issue that causes fouling in engines which hinders efficiency and power production.

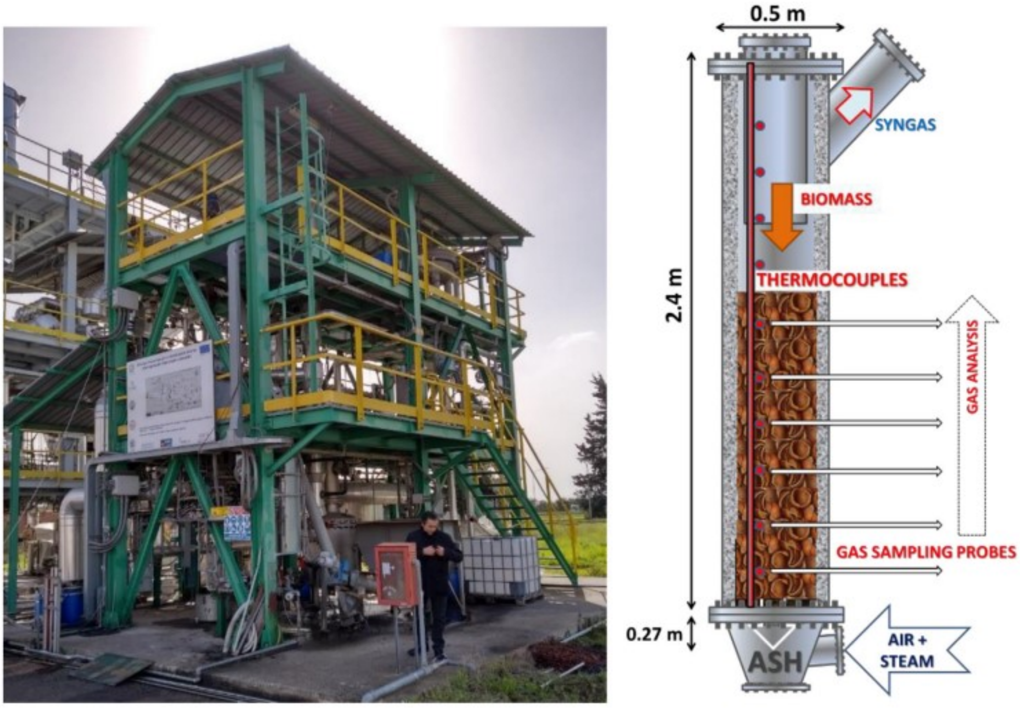


Figure 2.7: Updraft gasifier and schematic view of the gasifier used by (Cerone et al. 2020)

2.3.2 (ii) Downdraft Gasifier

Downdraft gasifiers operate in the opposite way of the updraft gasifier where the gasifying agent is supplied at the combustion zone which is located in the middle. Biomass passes from the top side to the drying zone where moisture is eliminated. Next, it is moved to the pyrolysis zone where the solid fuel is turned into gases and char. As these elements move along, the gasifying agent is fed, and the gases are then combusted. The main motive that is to maintain the temperatures of the gasification process is achieved at this zone. The biomass is then further moved into the reduction zone. The downdraft gasifier is also known as co-current gasifiers as the direction of gas and biomass flow are in the same direction. Downdraft gasifiers are more commonly used for small scaled applications as the most suitable type of gasifiers (Mishra and Upadhyay 2021). Figure 2.8 depicts the schematic diagram of a downdraft gasifier.