TUGAS AKHIR – TM4835

OPTIMASI PERFORMA GASIFIKASI PELEPAH KELAPA SAWIT PADA DOWNDRAFT GASIFIER MENGGUNAKAN MASUKAN UDARA TIGA TINGKAT

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2020

FINAL PROJECT – TM4835

GASIFICATION PERFORMANCE OPTIMIZATION IN A DOWNDRAFT GASIFIER USING THREE STAGE AIR INTAKE WITH PELLETIZED OIL PALM FRONDS FEEDSTOCK

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TUGAS AKHIR
Diajukan Untuk Memenuhi Salah Satu Syarat
Memperoleh Gelar Sarjana Teknik
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Januari, 2020

OPTIMASI PERFORMA GASIFIKASI PELEPAH KELAPA SAWIT PADA DOWNDRAFT GASIFIER MENGGUNAKAN MASUKAN UDARA TIGA TINGKAT

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ABSTRAK

Biomassa adalah salah satu sumber energi terbarukan yang paling menjanjikan. Gasifikasi adalah teknologi yang digunakan untuk mengonversi biomassa pelepah kelapa sawit (OPF) menjadi syngas yang dapat digunakan sebagai bahan bakar alternatif pada mesin diesel dan pembangkit listrik. Bahan baku OPF dijadikan pelet untuk meningkatkan kerapatan dan mengurangi kelembapan. Gasifier tipe downdraft digunakan karena memiliki laju produksi tar yang paling rendah. Tujuan dari riset ini adalah untuk mengoptimasi performa gasifikasi dalam parameter komposisi, laju produksi gas, LHV, efisiensi gas dingin, dan kandungan tar dari syngas menggunakan masukan udara tiga tingkat ke dalam zona pirolisis, oksidasi, dan reduksi.

Eksperimen ini dilaksanakan dengan menambah tiga tingkat masukan udara ke zona pirolisis, oksidasi, dan reduksi. Menggunakan ER 0,4, perbandingan laju masa udara masuk, yang dinyatakan dalam istilah AR (Air mass flow Ratio), pada zona pirolisis:oksidasi:reduksi divariasikan pada nilai 0 ; 10 ; 0 , 1 ; 6 ; 3, 2 ; 6 ; 2, 3 ; 6 ;1, 2 ; 5 ; 3, 3 ; 5 ; 2, 1 ; 8 ; 1, 2 ; 7 ; 1, and 1 ; 7 ; 2. AR yang dimasukkan ke tiap zona divariasikan menggunakan valve. Temperatur di sepanjang zona diukur menggunakan termokopel tipe K yang dipasang sepanjang tinggi reaktor. Kandungan tar diukur dengan menimbang berat tar yang terkondensasi pada timbangan. Laju produksi gas diukur langsung pada tabung pitot outlet. Komposisi syngas ditentukan melalui uji

Gas Chromatography. Efisiensi gas-dingin dihitung dari data hasil eksperimen.

Penggunaan masukan udara tiga tingkat pada zona pirolisis, oksidasi, dan reduksi diharapkan dapat menginisiasi reaksi pirolisis oksidatif dan oksidasi heterogen yang dapat menigkatkan komposisi, laju produksi, LHV, efisiensi gas-dingin, dan mengurangi kandungan tar dari syngas. Melihat penelitian sebelumnya, performa gasifier dihipotesiskan memuncak pada rasio 1:8:1.

Hasil dari penelitian menunjukkan adanya perubahan distribusi temperatur, dimana ada penurunan temperature di zona oksidasi dan kenaikan suhu pada zona pirolisis dan reduksi, masing-masing 124°C and 20°C pada titik paling puncak . LHV syngas maksimum sebesar 4524,97 kj/kg tercapai pada AR 1;7;2 dengan komposisi syngas CO: 21,12% v, H_2*: 12,39% v,* CH_4*: 1,33% v, dan* CO_2*: 10,90% v. Laju produksi gas tertinggi sebesar 0,00293 kg/s dicapai pada variasi AR 3;6;1. Efisiensi gas-dingin tertinggi sebesar 58,34% tercapai pada variasi AR 1;7;2. Kandungan tar terkecil sebesar 48,57* mg/Nm^3 *dicapai pada variasi AR 3;6;1.*

Keywords: gasification, three-stage ,OPF, performance

GASIFICATION PERFORMANCE OPTIMIZATION IN A DOWNDRAFT GASIFIER USING THREE STAGE AIR INTAKE WITH PELLETIZED OIL PALM FRONDS FEEDSTOCK

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ABSTRACT

Biomass is one of the most promising source of renewable energy. Gasification is the technology used to convert Oil Palm Fronds (OPF) biomass into syngas that can be used for alternative fuel in diesel engines and electricity generation. OPF feedstock was pelletized to increase feedstock compactness and reduce moisture content. Downdraft gasifier was used due to having the lowest tar content in its product. The objective of this research was to optimize gasification performance in terms of composition, gas production rate, LHV, cold-gas efficiency, and tar content of the syngas by using three stage air intake into the pyrolysis, oxidation, and reduction zones.

The experiment was performed by introducing three stages of air intake into the pyrolysis, oxidation, and reduction zones, respectively. Using ER of 0,4, the ratio of the air inlet mass flow, which is stated in the term of AR (Air mass flow ratio) of pyrolysis:oxidation:reduction zones, was varied at the values of 0 ; 10 ; 0 , 1 ; 6 ; 3, 2 ; 6 ; 2, 3 ; 6 ;1, 2 ; 5 ; 3, 3 ; 5 ; 2, 1 ; 8 ; 1, 2 ; 7 ; 1, and 1 ; 7 ; 2. The AR injected into each zones are adjusted using valves. The temperature distribution along the height of the reactor measures by type K thermocouples installed along the height of the reactor. The tar content is measured by weighing the condensed tar on the weight balance. Gas production rate is directly measured from the outlet pitot tube. The *composition of syngas is determined through gas chromatography test. Cold-gas efficiency is calculated from experiment result data.*

The use of three stage air intake into the pyrolysis, oxidation, and reduction zones is expected to result in the initiation of oxidative pyrolysis and heterogeneous oxidation reactions which will subsequently increase the composition, production rate, LHV, cold-gas efficiency, and reduce tar content of the syngas. Considering previous researches, the performance of the gasifier is hypothesized to peak at 1:8:1 ratio.

The results of the study showed that there was a change in the temperature distribution, where there was a decrease in temperature in the oxidation zone and the temperature increase in the pyrolysis and reduction zones, by 124°C and 20°C at their respective peak points . Maximum syngas LHV of 4524,97 kj/kg is achieved at 1;7;2 AR variation with the syngas composition of CO: 21,12% v, H_2: 12,39% v, CH_4: 1,33% v, and CO_2: 10,90% v. The highest gas production rate achieved was 0,00293 kg/s at 3;6;1 AR variation. The highest Cold-Gas efficiency of 58,34% was achieved at 1;7;2 AR variation. The lowest tar content of 48,57 mg/Nm^3 achieved at 3;6;1 AR variation.

Keywords: gasification, three-stage ,OPF, performance

Preface

This undergraduate thesis under the title of **“GASIFICATION PERFORMANCE OPTIMIZATION IN A DOWNDRAFT GASIFIER USING THREE STAGE AIR INTAKE WITH PELLETIZED OIL PALM FRONDS FEEDSTOCK”** has finally been completed successfully.

Undergraduate thesis is one of the obligatory task that must be fulfilled by every ITS Undergraduate Mechanical Engineering Department, Surabaya student, as legally set in the student’s rulebook. Moreover, this thesis will also be considered a token of service and dedication towards the common public.

Much help has been received by the writer during the construction of this thesis. For such generosity, the author would like to offer their deepest and sincerest gratitude towards the following individuals:

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May all of their sincerity and kindness be repaid in the best of ways.

For the time is short and so is the inspiration. The author realizes that this writing still has its shorts and flaws. Thus, critics and suggestions are always welcome and expected by the author. For without which, this thesis would never be something even near the word complete. And may this writing be helpful for anyone who needs or intends to develop it.

Surabaya, 27 Januari 2020

Author

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CHAPTER I

INTRODUCTION

1.1 Background of Research

Biomass energy is one of the most promising source of renewable energy nowadays. In Indonesia alone, biomass energy has a potential of 32,654 MW which is currently utilized by only 5.1% which is about 1,671 MW (RUEN, 2017). This is actually quite unfortunate since the government of Indonesia has targeted the use of renewable energy by 23% of total energy production by the year 2025. Hence, all the more reason to develop and extend the research on renewable energy, especially biomass. Currently, agricultural and municipal domestic waste comprise most of the source of biomass. Indonesia is by far the largest producer of palm oil in the world, and this number keeps growing due to ever-rising areas of oil palm plantation in the country. As a figure, according to Tree Crop Estate Statistic of Indonesia 2015-2017 (2016) on Palm Oil published by Directorate General of Estate Crops of Indonesia, the current total combined oil palm plantation area is estimated to be around 11,914,499 Ha with a total production of 33,229,381 tons of Crude Palm Oil (CPO) as of December 2016 with Sumatran Provinces which has the largest area of plantation with approximately 7 million Ha with total CPO production of 7,032,857 tons, followed by Borneo, Sulawesi, and Java. Unfortunately, with such extensive number of palm oil production, comes extensive number of waste production and problems. One of the most frequently wasted part of Oil Palm is its leaf fronds (OPF). OPF constitutes 46.71 % of total waste produced by oil palm fruit processing which most of the times are rarely repurposed. For example, during oil palm harvest, it is simply dried and burned, or simply left on the ground to decompose, mainly for soil fertilization and erosion control. Due to its constant availability and large amount of supply, OPF can potentially be a reliable source of renewable energy in the future. However, the solid biomass properties of OPF including its bulky heterogeneous nature, low bulk density, and localized supply presents problems for large scale commercial bioenergy power conversion projects which is why OPF-based power generation is relatively suitable only for local applications. To tackle this problem, there are several methods of energy conversion available which can be applied using OPF. Biomass gasification is one of them. From previous experiment (Sulaiman *et al*, 2014) shows that gasification of OPF shows promising results with produced Syngas containing 22.78% of CO, 11.81% of CO_2, 2.02% of CH_4, 8.47% of H_2, and Syngas Higher Heating Value (HHV) of 4.66 MJ/Nm^3 which is comparable to that of other biomass products. This shows that OPF is suitable to use with gasification method.

Biomass gasification is a thermal conversion of solid biomass through partial oxidation using medium such as air, steam, or pure oxygen, to produce usable gaseous fuel which is called *Syngas*, and a solid product, called char (Molino, 2015). Gasification process reduces carbon content of fuel product and rejects non-combustible components such as nitrogen and water away from the feedstock to produce gases with higher hydrogen-to–carbon (H/C) ratio (Basu, 2010). A general biomass gasification process consists of 4 steps: (1) Drying (endothermic), (2) Thermal decomposition or Pyrolysis (endothermic), (3) Partial combustion/oxidation of some gases, vapors, and chars, and (4) Reduction (endothermic). Medium for gasification are mainly pure oxygen, steam, or air. Gasification results in gaseous fuel, which is called *Syngas,* which consists of carbon monoxide (CO), Hydrogen (H_2), Methane (CH_4), and carbon dioxide (CO_2). Medium used for gasification directly affects its results since the contents of produced syngas come from various reactions (Carbon reaction, oxidation, methanation, etc.) that occur within the reactor which will be further explained later in this thesis, which directly involves the O_2 and H_2O contents of medium. For example, the use of pure oxygen may produce *syngas* which is rich in CO_2 and lean in CO since O_2 rich medium triggers more oxidation reaction, resulting in more CO_2 being produced.

When a non-pyrolyzed fuel is used in gasification, hydrocarbons (tar) will form. Tars consist of a range of oxygenated hydrocarbons and hydro-carbons, typically containing aromatic, polyaromatic, and furanic backbone structures, with aliphatic and oxygenated functional groups (acids, aldehydes, ketones, and alcohols) attached to the backbone (Huang, et al, 2011). Tar condenses at the temperature of 200-500 °C which can lead to plugging or break down of the subsequent processes such as filters, engines, turbines or fuel cells therefore it can be necessary to remove or crack the tar content. (Fjellerup, *et al*, 2005). Different sources use different allowable levels of tar contents for syngas application. For example, in a journal by T bui, *et al*, 1994, the allowable tar content inside syngas for engine is below 10 mg/Nm^3, in a book by Basu, 2010, it is below 100 and 0.1-120 mg/Nm^3 for internal combustion engines and gas turbines respectively, and in a journal by Fjellerup, *et al*, 2005, it is about 50, 5, and 1 mg/Nm^3 for gas engines, gas turbines, and fuel cells, respectively. To overcome this numerous methods have been experimented to reduce tar content inside syngas. Methods of tar reduction are divided into two kinds, primary and secondary methods. Primary methods are methods performed in the reactor itself, reducing tar during its formation, whereas secondary methods are methods performed outside the reactor, done on the resulting syngas. Previous experiments being done in ITS have focused on primary methods. One of the methods is the choice of reactor type. Based on the direction of yield flow, gasification reactors/gasifiers are divided into 3 types of configuration, updraft, in which the output syngas flows in counter-current with the fuel (upward), downdraft, in which the output syngas flows in co-current with the fuel (downdraft), and crossdraft configuration, in which the output gas flows sideward across downward-moving fuel through a side mounted outlet, which is placed face to face with the intake passage. Out of these commonly known types of reactors, this experiment used a downdraft type gasification reactor. This type of reactor is chosen because it has lowest tar production rate out of all fixed bed type reactors, due to its configuration in which tar-containing syngas goes out from below the reactor through hot ash residue, which will increase the rate of tar decomposition process, which will be further explained later, and it is inexpensive to build and operate, suitable for small scale reactors. (Basu, 2010).

Another method which has been commonly used and currently being further developed is multi stage medium input. This method utilize multiple air inlet on different zones/part of reactors. Previous experiments in ITS showed that using multi stage air inlet yielded better results in terms of syngas composition and Low Heating Value (LHV). For example, in a thesis by Gafur, 2018, using oil palm frond (OPF) biomass as fuel, showed that, in dual inlet reactor configuration, by increasing the amount of air into the pyrolysis zone, the yielded syngas has CO content changed from 16.52 to 22,52 %v, CH_4 dari 1,65 to 0,97 %v, and H_2 dari 13,22 to 15,49%v, with syngas LHV increased from 4106 kJ/Nm^3 to 4822 kJ/Nm$^{3.}$compared to when using single air inlet into oxidation zone. In terms of tar content reduction, multi stage air inlet also showed the same positive result. In the same experiment by Gafur, 2018, the lowest tar content achieved was 37 mg/Nm^3 with inlet ratio of Pyrolysis/Oxidation zone ($AR_{Pir-Oks}$) of 90% on 0.5 Equivalence Ratio compared to 386.7 mg/Nm^3 achieved with $AR_{Pir-Oks}$ of 0% on 0.3 Equivalence Ratio. In another experiment by Guterres, 2018, also in ITS, using municipal solid waste (MSW) biomass as fuel, increasing the amount of air into the reduction zone to a certain degree also improved the syngas yield of the reactor. It was stated in his thesis, that by increasing the amount of air into the reduction zone by about 10% of the total air intake, the flammable content of the syngas increased from having CO of 17,58%, H_2 of 10,04%, and CH_4 1,02% to CO 18,03%, H_2 11,1%, and CH_4 1,15% respectively compared to 0% reduction zone air intake. In terms of syngas LHV, the LHV increased from 3563 kJ/kg at 0% reduction air to 3788 kJ/kg at 10% reduction air intake. Also, in terms of tar content, the lowest tar content was also reduced to 66.91 mg/Nm^3 at 10% reduction air compared to 153.87 mg/Nm^3 at 0% reduction air intake. Ximenes, 2018, also performed another experiment using MSW biomass but instead of two stage gasifier, he used three stage downdraft gasifier as the equipment. The experiment showed that by increasing the additional amount of air intake into both the pyrolysis and reduction zone to a certain degree, gasification process could be optimized. This was shown in his experiment result data, which states that using air intake ratio of 1:8:1, with each ratio number showing the ratio of air mass flow into pyrolysis:oxidation:reduction zones respectively, the LHV and cold-gas efficiency of the resulting syngas increased compared to not injecting additional air into the pyrolysis and reduction zone (0:10:0 ratio), with the increased value being from 3563 kJ/kg to 4034 kJ/kg for LHV and 60,53% to 70% for cold-gas efficiency. The tar content of syngas was also reduced from 146,98 mg/Nm^3 to 57,29 mg/Nm^3.

Based on the explanation above, this experiment will be performed with a downdraft gasifier utilizing three stage air intake using pelletized oil palm frond (OPF) biomass as the fuel. Three stage air intake will be placed on the pyrolysis, oxidation, and reduction zone. To determine the placement of the aforementioned intake passages, gasification zones will be determined from temperature profile in the gasifier beforehand using pre-placed thermocouples on the gasifiers. This three stage air intake method is used to improve the gasifier’s temperature profile and the quality of syngas content for the purpose of achieving syngas tar content of lower than 100 mg/Nm^3 (Milne, 1998).

1.2 Research Problem

The problem in the research can be stated as: how does three stage air intake in pyrolysis, oxidation, and reduction zones affect gasification performance optimization in terms of composition, production rate, LHV, cold-gas efficiency, and tar content of the resulting syngas.

1.3 Research Scope and Limitation

Scope and limitations which apply in this research can be stated as follows.

1. This research will be performed experimentally using laboratory scale downdraft gasifier provided in Department of Mechanical Engineering ITS Surabaya.
2. The feedstock used in this research is oil palm fronds pellets with predetermined size and moisture.
3. The free air used as gasification medium is assumed to be in normal atmospheric condition. (1 atm, 25 °C).
4. Loss of heat from the reactor into the environment is ignored.

1.4 Research Objectives

The objective of this research can be stated as: Knowing how three stage air intake in pyrolysis, oxidation, and reduction zones affects gasification performance optimization in terms of composition, production rate, LHV, cold-gas efficiency, and tar content of the resulting syngas.

1.5 Benefit of Research

The benefit of this research can be stated as follows:

1. Contributing new information and reference in the betterment of gasification technology.
2. Encouraging use of renewable energy.
3. May be used as a reference for further research in downdraft gasifier and OPF feedstock gasification.

CHAPTER II

REVIEW AND STUDY OF LITERATURES

2.1 Biomass and Its Properties

Biomass refers to any form of non-fossil and biodegradable organic materials originating from plants, animals, and micro-organisms, including their by-products, residues, and waste (Basu, 2010). Biomass is formed through the interactions of environmental factors, such as air, water, soil, or sunlight, and organic materials originating from living organisms. To understand biomass potentials in energy generation, the understanding of its traits and characteristics is required. Biomass generally consists of complex organic compounds such as cellulose, hemicellulose, lignin, and some other organic molecules, moisture, and a small amount of inorganic contents known as ash. To determine the actual contents of biomass, series of analysis must be performed, which generally consist of *proximate* and *ultimate* analysis, and heating value analysis.

Proximate analysis produce results which give the composition of biomass in terms of general/gross components such as moisture, volatile matter, ash, and fixed carbon. This analysis is a relatively simple process and may tell the general characteristics of a biomass. Moisture refers to the amount of water content diffused into the biomass. Moisture content of a gasification biomass feedstock may greatly affect performance of a gasification plant since the energy which is supposedly used for biomass thermal conversion is given away to evaporate the moisture content. Volatile matter is the amount of condensable and incondensable vapour released when fuel is heated. Its amount depends on the rate of heating and the temperature to which it is heated. Volatile matter mainly shows the ignitability and susceptibility of fuel when being ignited. Ash is the inorganic substance left after fuel is completely burned. It mainly consists of silica, aluminium, iron, and calcium, yet other inorganic minerals may also be found such as magnesium, titanium, sodium, or potassium. Ash mainly comes from impurities found within the biomass itself, but may also come from outside factors such as dirt and rocks scraped off the ground by the biomass itself during collection and handling. Fixed carbon is the amount of carbon remaining in the char of the biomass after devolatilization. Fixed carbon content plays a huge role in biomass gasification since it determines the amount of carbon being converted into gases, hence determining gasification rate and its yield. Ultimate analysis on the other hand, focuses on analyzing fuel composition in terms of its basic elements except for its moisture and inorganic contents (ash, etc.). Typical ultimate analysis results in form of weight percentage of fuel basic elements such as C (Carbon), H (Hydrogen), O (Oxygen), N (Nitrogen), and S (Sulfur). Note that the majority of biomass may contain little to no sulfur content inside them. This percentage of elements summed with Moisture (M) and Ash content will result in 100% of fuel weight percentage. Heating value analysis on the other hand, analyse the amount of energy released by fuel during its combustion/oxidation process, which directly states the amount of energy it contains. Biomass fuel has less heating value compared to its fossil counterpart due to its low density mainly caused by its porous and hollow inner structure. Based on its definition, heating value is divided into two types: High Heating Value (HHV) and Low Heating Value (LHV).

a. High Heating Value (HHV)

   HHV is defined as the amount of heat released by 1 kg of fuel (SI unit) on its combustion. HHV is calculated from its initial temperature (room temperature, assumed ~25°C) until its final temperature returns to the same value as its initial temperature, which includes the heat released during condensation of water since its final temperature is equal to its initial temperature.

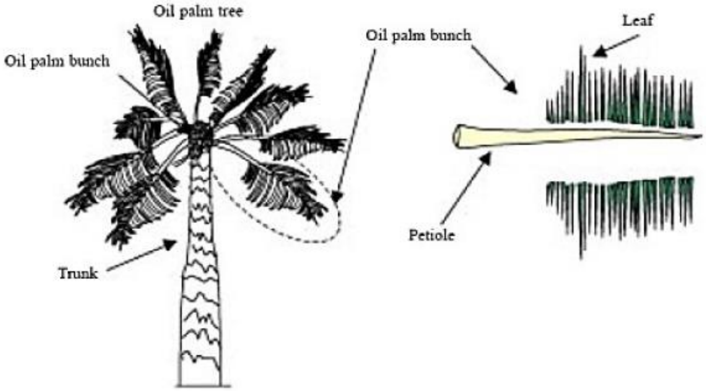
b. Low Heating Value (LHV)

LHV has the same definition as HHV but instead of doing the calculation of heat release up to returning to initial temperature, the final temperature is defined as a temperature above water vaporization temperature, therefore the latent heat of water vaporization is not recovered. In other word, LHV is defined as the amount of heat released by fully combusting a specified quantity less the heat of vaporization of water in the combustion product (Basu, 2010).

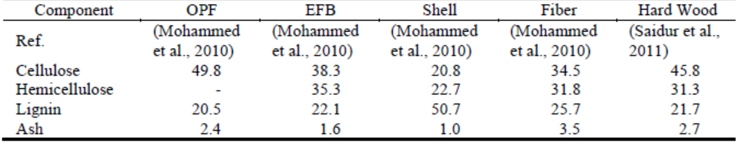
The relationship between HHV and LHV is given by:

$$LHV = HHV - h_g\left(\frac{9H}{100} + \frac{M}{100}\right)$$

One of the most potentially productive biomass, which will be used in this research, is OPF (Oil Palm Fronds), a waste product which comes from oil palm products processing industries. Waste management of this type of waste has up until now been, relatively speaking, poorly done. Common treatments for OPF in most plantations have largely been mere incineration, which produces a lot of emission and air pollution, or simply left on the ground to dry and decompose, mainly for soil fertilization purposes. Recent studies show that OPF is suitable to use in biomass energy generation plants. (Sulaiman, *et al*, 2015) study shows that from average proximate analysis result of a finely ground OPF biomass, OPF has low moisture content, around 4% weight, volatile matter content at around 51% weight, considered moderate, fixed carbon content of around 38% weight, and ash content of around 6%, which is very low compared to other types of biomass, such as straw (8%), cane (11%), cotton stalk (14%) and rice husk (18%). Average calorific value of OPF was also reported to be around 22,868 kJ/kg, which makes OPF a considerable choice in choosing biomass fuel for gasification and other thermal conversion methods, compared to other biomass.



(a)



Component	OPF	EFB	Shell	Fiber	Hard Wood
Ref.	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Mohammed et al., 2010)	(Saidur et al., 2011)
Cellulose	49.8	38.3	20.8	34.5	45.8
Hemicellulose	-	35.3	22.7	31.8	31.3
Lignin	20.5	22.1	50.7	25.7	21.7
Ash	2.4	1.6	1.0	3.5	2.7

(b)

Figure 2.1. (a) Oil Palm Frond morphology (b) Biomass chemical composition (Sulaiman, *et al,* 2011/2015)

Furthermore, OPF is high in cellulose content, which is favourable for gasification processing, since cellulose is reported to have higher carbon monoxide yield and carbon conversion rate, yet low in ash and lignin content (2,4% and 20,5% respectively) (Sulaiman, *et al,* 2011). This proves that OPF is suitable for use in gasification processing.

2.2 Biomass Conversion Technology

Normally, untreated biomass by itself could directly be used as fuel for combustion. Yet, many obstacles emerge when we try to consider biomass as a potential, sustainable replacement for fossil fuel. For instance, biomass has a bulky and inconvenient form which may pose a problem during transport, handling, or storage. Hence, methods of biomass conversion into forms more suitable for practical use, for example gaseous or liquid forms, have been studied. So far, biomass conversion can be achieved through two major paths: biochemical (fermentation), and thermochemical conversion.

Biochemical conversion utilize the work of bacteria and enzymes to break down the molecules of biomass into smaller molecules and lighter forms such as gas or liquids. This method doesn’t require much external energy yet the process runs relatively slowly. There are three major routes for biochemical: digestion (anaerobic and aerobic), fermentation, and enzymatic/acid hydrolysis conversion. Digestion occur in the presence of free oxygen (aerobic) or bound oxygen (anaerobic) found in the biomass itself. Digestion commonly result in gaseous form of products such as methane and CO_2 (anaerobic), or solid and gaseous mixture forms (aerobic) such as CO_2, and solid digestate. Fermentation converts biomass into sugars using acid or enzyme, then further converted into ethanol and other chemicals with the help of yeast fungi. Unlike in anaerobic digestion, the product of fermentation is liquid. Enzymatic/acid hydrolysis conversion is required for cellulosic biomass, such as wood, to break down cellulose and hemicellulose content into simple sugars needed by yeast and bacteria for fermentation process to produce ethanol.

Thermochemical conversion on the other hand, converts biomass at a certain temperature with or without the help of catalysts, to stimulate certain reactions which convert biomass into various gases, which are then used directly, or further converted into other desired chemicals. So far there are four major routes for biomass thermochemical conversion: combustion, pyrolysis, gasification, and liquefaction (Basu, 2010). Combustion converts biomass into CO_2 and water vapour in high temperature condition in the abundant presence of oxygen. Pyrolysis takes place in the total absence of oxygen to produce solid chars, various gases, and/or some liquid fuel called bio-oil. Gasification occurs at a high temperature and an oxygen-deficient environment, involving various chemical reaction to convert biomass into various useful gases and chemicals. Liquefaction decomposes large biomass molecules into liquid with smaller molecules in the presence of a catalyst in a relatively low temperature.

2.2.1 Gasification

Gasification is a method of biomass thermal conversion in the presence of substoichiometric air which converts biomass with carbon content into conveniently usable gaseous fuel. This gas may be used for various purposes, like power generation or biofuel production, since it can be processed further to produce value-added chemicals, as shown in the figure below.

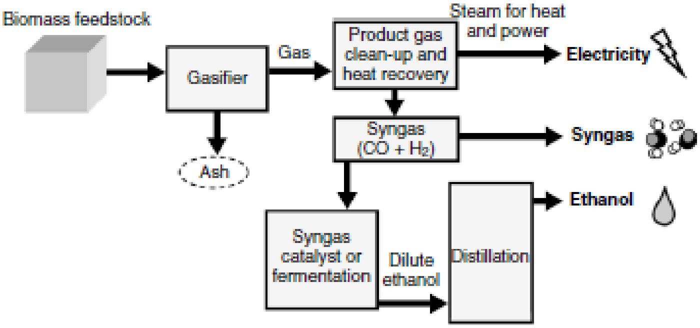


Figure 2.2. Thermochemical route for gasification derivative products.

Gasification medium affects the end results of gasification. They react with the fuel then convert it into lighter molecules of gases (syngas). There are three common mediums for gasification: pure oxygen, free air, and steam, each with their own characteristics which affects the produced syngas. Mainly, the contents within the medium that affect gasification result are oxygen and hydrogen contents. Pure oxygen tend to stimulate more oxidation reaction. Too much of it will in turn produce more flue gas which contains more carbon content such as CO_2. Steam on the other hand, contains more hydrogen content in H_2O vapour, which will increase syngas H/C content ratio. Free air contains more nitrogen, which will negatively affects the heat value contained in syngas, yet it is the easiest medium to acquire and use compared to other mediums.

Table 2.1, Main chemical reactions of biomass gasification (Sutton, et al, 2001)

Description	Reaction	ΔH 298,kJ/mol
1. Partial oxidation of solid carbon	$C+0.5O_2=CO$	−111
2. Complete oxidation of solid carbon	$CO+O_2=CO_2$	+402
3. Oxidation of hydrogen	$H_2+0.5O_2=H2O$	−242
4. Water gas reaction (char reforming)	$C+H_2O=CO+H_2$	+131
5. Boudouard reaction	$C+CO_2=2CO$	+172
6. Methanation reaction	$C+2H_2=CH_4$	−75
7. Methanation reaction	$CO+3H_2=CH_4+H_2O$	−206
8. Methanation reaction	$CO_2+4H_2=CH_4+2H_2$	−165
9. Water gas shift reaction	O $CO+H_2O=CO_2+H_2$	−41

With insufficient amount of gasification medium during gasification, substoichiometric condition is achieved, and partial oxidation occurs. Partial oxidation combined with high temperature causes thermal decomposition of biomass through various reactions, as stated in the table below, producing gases such as CO, CO_2, N_2, O_2, H_2, and CH_4, which is collectively called "syngas". Syngas usually has LHV ranging from 4 to 13 MJ/Nm^3 depending on the feedstock, gasification technology used, and the operational conditions (Molino, 2015).

2.2.2 Gasification Working Principles

Gasification process involve numerous chemical reactions as stated in the table above. These chemical reactions set apart gasification process from combustion, in which fuel's molecules chemical bonds are broken to release energy, resulting in carbon dioxide and water vapour (stoichiometric combustion), which also explains the exothermic nature of combustion process, whereas gasification processes are mainly endothermic processes, save for few processes, for example, the char oxidation process, as seen in the table. In this case, energy needed by gasification endothermic processes are provided by exothermic processes. This type of process mechanism is called autothermal process in contrast to allothermal process, in which energy needed by the processes is supplied through external means (Basu, 2010).

Gasification process typically consists of following steps:

a) Drying (endothermic)
b) Pyrolysis (thermal decomposition - endothermic)
c) Oxidation (substoichiometric combustion - exothermic)
d) Reduction (gasification – endothermic)

2.2.2.1. Drying

Drying process is defined as the endothermic vaporization of moisture contained within biomass. Biomass moisture is one of major obstacles to sustainable biomass energy conversion, due to immense amount of energy consumed during this process. On average, common biomass contains 30-60% of moisture content, and every kilogram of which consumes irrecoverable 2260 kJ of extra energy from the gasifier to vaporize the water content. Which is why, predrying process is vital for biomass gasification to reduce energy consumption during drying step.

Drying process starts at above 100 °C of temperature and ends at around 200 °C. Due to such low temperature, thermal decomposition does not occur in this step. As it is called, the only reaction occurs in this step is water vaporization, written as:

$$\text{Biomass} + H_2O(l) \rightarrow \text{Dried biomass} + H_2O(g)$$

2.2.2.2. Pyrolysis

Process that occurs after drying is called pyrolysis. It occurs at around 200-900 °C depending on the desired yield. In this process, thermal decomposition occurs, normally without the presence of free air/gasifying medium, resulting in products such as solid char (carbon), liquids such as tars, water, or heavier hydrocarbons, and gases, mainly condensable gas (vapour) and non-condensable gas (primary gas), such as CO, CO_2, CH_4, C_2H_4, C_2H_6, etc. or secondary gases, if condensable gas is held inside the pyrolysis zone long enough to react with biomass feedstock. Pyrolysis is an endothermic process in nature. Reactions in this step may be described as:

Dried biomass + heat→ Primary/secondary gas + Liquids (tars, water, hydrocarbon oil, etc.) + Solids (*Char)*

2.2.2.3. Oxidation

Oxidation process/combustion has an exothermic nature, which makes it the main source of heat energy for the rest of gasification processes. Oxidation is allowed in a gasifier only to a certain extent, since, excess of oxidant will unnecessarily raise the gasifier temperature, as well as reduce the quality of produced syngas by diluting it with excess CO_2. Hence, oxidation process in a gasification process is preferred to be in the form of partial oxidation, which not only provides heat for the rest of the gasifier, but also increase syngas yield by producing CO. Reactions involved in gasification oxidation process may be described as:

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -394 \text{ KJ/mol}$$

(Char combustion)

$C + \frac{1}{2} O_2 \rightarrow CO$ $\Delta H = -111$ KJ/mol
(Char-Oxygen/partial oxidation)

$CO + \frac{1}{2} O_2 \rightarrow CO_2$ $\Delta H = -284$KJ/mol
(Complete oxidation)

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ $\Delta H = -242$ KJ/mol
(Hydrogen oxidation)

2.2.2.4 Reduction

Reduction step involve all products produced in the previous steps of gasification, various gases and chars, to react with each other and produce the end product, syngas. The main reactions which occur during this step are:

a. *Bouduard* reaction

Bouduard reaction is an endothermic reaction involving carbon from chars produced in pyrolysis step, and CO_2 from combustion to produce CO. The reaction is described as:

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = +172 \text{kJ/mol}$$

b. Water-gas reaction (char reforming)

Water-gas reaction is an endothermic reaction which involve the chars produce from pyrolysis and H_2O vapour from various source to produce CO and H_2. The reaction is described as:

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = +131 \text{kJ/mol}$$

c. Water-gas shift reaction

Water gas shift reaction is an exothermic reaction involving CO and H_2O vapour to produce CO_2 and H_2.

This reaction increases the amount of H_2 compared to CO content contained in the syngas product. The reaction is described as:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41 kJ/mol$$

d. Methanation reaction

Methanation is an exothermic reaction which forms methane involving chars and synthesized H_2 from previous reactions. The reaction is described as:

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H = -75 kJ/mol$$

The composition of syngas formed by the balance of reactions described above is also directly affected by the temperature within the reduction zone. Certain temperature tends to favour which product of reactions will dominate within the composition of syngas product, which means certain temperature will stimulate certain reactions to occur more compared to others. Theoretically, the endothermic reactions (*Bouduard* and char reforming reactions) will be favoured in higher temperature (> 900 °C) compared to other reactions. While in lower temperature, exothermic reactions (shift and methanation reactions) tend to occur more often. But in the other hand, higher temperature tends to increase syngas yield and reduce tar formation, yet it risks slag and ash formation which can potentially reduce the heating value of syngas. These effects may be described in the figure below:

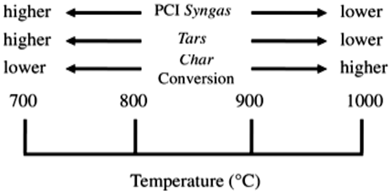


Figure 2.3. Temperature effects in syngas characteristics (Molino, *et al*, 2015)

2.2.3 Gasifier

Reactor used to perform gasification operation is called gasifier. Most gasifiers are designed to process fluidized feedstock, rather than batch operation. There are several types of gasifier commonly based on the flow of the feedstock, or the means of contact between gasifying medium and the feedstock itself. Each type of gasifier has their own advantageous range of operation. Based on the flow of the feedstock, gasifier is divided into two types, fixed bed gasifier, in which the feedstock is set on a fixed position on a feedstock grate, and fluidized bed, in which the feedstock is fluidized by the gasifying medium over the fluid bed during gasification process. The type of gasifier used in this research is a downdraft fixed-bed gasifier. More types of gasifier may be seen in the figure below.

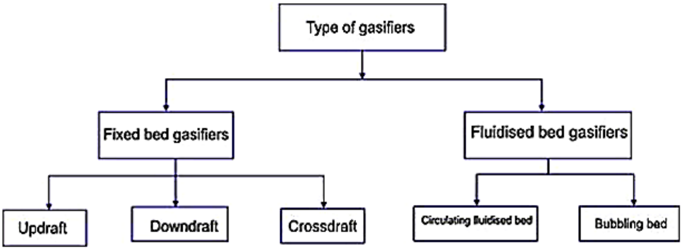


Figure 2.4. General classification of gasifiers.

2.2.4 Fixed Bed Gasifier

Fixed bed gasifier is a type of gasifier in which the biomass is seated on a fixed grate for further processing in gasification. The feeding direction of fuel and gasification process tend to head downward, with the waste product, ash, is discharged towards the bottom of reactor. Based on the direction of contact between the gasifying medium and the feedstock, fixed bed gasifier is commonly divided into three types: Updraft, Downdraft, and Crossdraft gasifiers.

2.2.4.1. Updraft Gasifier

Updraft gasifier is a type of gasifier in which the feed direction of biomass fuel and the flow of the syngas product go in opposite of each other.

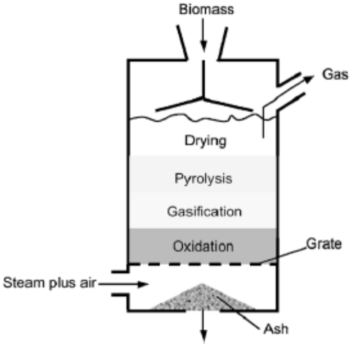


Figure 2.5. Updraft gasifier

With the product syngas flows in from the lower part of the gasifier, through hot bed of ash, upward, exiting through the top passage of the gasifier. This type of gasifier produces syngas with relatively high tar content (30-150 g/Nm^3), rendering its product unsuitable for storage or later use purposes.

2.2.4.2 Downdraft gasifier

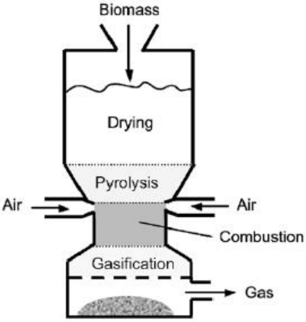


Figure 2.6. Downdraft Gasifier

Downdraft gasifiers has the exact opposite reactor configuration compared to that of updraft gasifiers. The fuel feedstock flows downward in parallel with the gasifying medium, with the syngas product exiting from below the gasifier through the bed of ash. This type of gasifier has the zone of gasification (reduction zone) below the oxidation zone, the pyrolysis zone above it and the hot bed of ash on the bottom of the reactor. This makes the produced syngas created from the reduction zone have to pass through high temperature bed of ash before exiting. This lowers the tar content of the syngas product by the means of tar cracking, which makes the syngas product of this type of reactor suitable for storage and long-term use.

2.2.4.3 Crossdraft Gasifier

Crossdraft gasifier has an entirely different configuration compared to the other two types of fixed bed gasifiers.

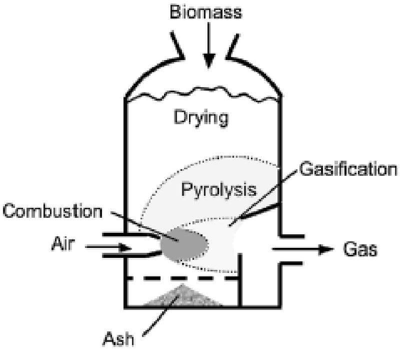


Figure 2.7. Crossdraft Gasifier

This type of gasifier has the fuel fed downward from the topside, the intake air injected from the side part of the gasifier at certain height above the grate, and the product exit from the other side of the gasifier, which makes the air and gas flow quite faster through the reactor, resulting in faster reaction time and response to load changes, suitable for direct use of the syngas product.

2.2.5 Multi-stage air intake in gasifiers

Syngas produced from a gasifier must meet certain conditions to qualify as a sustainable fuel. Traditional gasifiers with single inlet (single stage) had commonly been used in the past to produce syngas for alternative fuel. But, it was known afterwards, that the syngas produced from such type of reactor contained quite high tar content (~2g/Nm^3 for traditional downdraft configuration, Bhattacharya, et al, 1993), hence its product became unsuitable for direct use with for example, internal combustion engine, limiting its application. For this reason tar reduction methods have been researched. For usability and practicality purposes, primary methods of tar reduction are preferred over secondary methods. Multi stage air intake is one of the primary methods intensively researched for aforementioned purpose. Multi stage air intake simply means the addition of air intake into different zone/zones of gasification besides the oxidation zone. Former researches had found, that utilizing multi stage air intake results in higher operating temperature of the gasifier, favouring thermal cracking of produced tar. Multi stage gasifiers have been previously researched in various configuration, mainly two staged or three staged.

For example, in ITS, a two stage intake downdraft gasifier, each in oxidation and pyrolysis zone, was previously studied in 2018 by Abdul Gafur. The amount of air added into the pyrolysis zone ranged from 0% to 90% compared to oxidation air intake. In this experiment, it was known that the distribution of temperature along the reactor increased when an additional air is introduced into pyrolysis zone with the highest temperature profile achieved at an Equivalent Ratio (ER) of 0.5 and an air intake ratio of pyrolysis-oxidation zone ($AR_{Pir-Oks}$) at 90%. In another experiment in ITS by Guteres, 2018, additional air intake in two stage downdraft gasifier was introduced into the reduction zone. The amount of air introduced into the reduction zone ranged from 0% to 40% of total air intake. It was shown in this experiment that by introducing a certain amount of air into the reduction zone, the temperature of reduction zone increased by about 48 °C albeit with the slight reduction of temperature in the oxidation zone. Ximenes, 2018, also performed another experiment using MSW biomass using three stage downdraft gasifier as the equipment. The experiment showed that by increasing the additional amount of air intake into both the pyrolysis and reduction zone to a certain degree, gasification process could be optimized. This was shown in his experiment result data, which states that using air intake ratio of 1:8:1, with each ratio number showing the ratio of air mass flow into pyrolysis:oxidation:reduction zones respectively, the LHV and cold-gas efficiency of the resulting syngas increased compared to not injecting additional air into the pyrolysis and reduction zone (0:10:0 ratio), with the increased value being from 3563 kJ/kg to 4034 kJ/kg for LHV and 60,53% to 70% for cold-gas efficiency. The tar content of syngas was also reduced from 146,98 mg/Nm^3 to 57,29 mg/Nm^3

From the statement above, we may hypothesize that by adding a certain amount of air into the reduction and pyrolysis zone, the overall temperature profile of gasifier may increase which will presumably favour the thermal decomposition reaction which will increase gas composition and reduce tar content in the resulting syngas.

2.2.5.1. Oxidative Pyrolysis

2.2.5.1.1 Pyrolysis Definition

Pyrolysis commonly means a process of thermal decomposition of carbon-based fuel into gas, liquid, and solid products, either with total absence of oxygen, or limited supply of oxidizing agent in permissible amount for self-sustaining energy, for pyrolysis is normally an endothermic process which needs external energy to perform. Pyrolysis is typically carried out in a temperature ranging from 200 to 900 °C depending on the used feedstock or desired products. During pyrolysis, large, complex hydrocarbon molecules of fuel are broken down into smaller, simpler molecules of gas, liquid, and char. The process involved in pyrolysis may include devolatilization, thermal cracking, carbonization, dry distillation, and thermolysis.

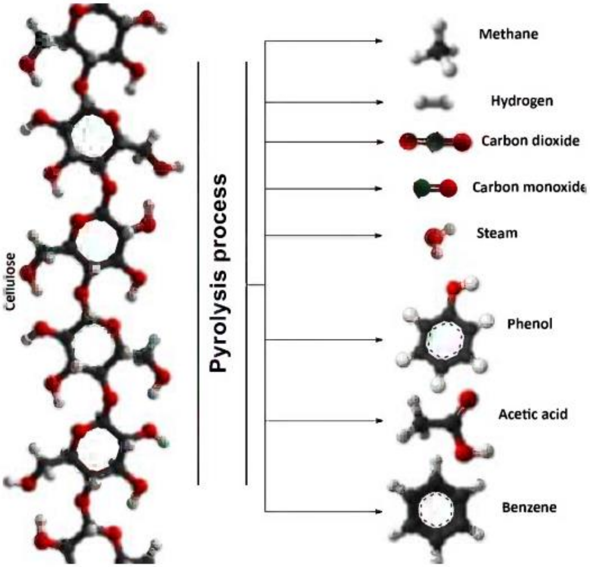


Figure 2.8. Large hydrocarbon molecules decomposition during pyrolysis (Basu, 2010).

2.2.5.1.2. Pyrolysis Products

Pyrolysis results in products in the form of gas, liquid, and solid. Gases in form of condensable (vapour) and non-condensable gases (primary gas), liquid in form of tars, water, or bio-oil, and solid in form of chars. These products yield depends on different factors such as the chemical and physical composition of the feedstock, heating rate, pyrolysis temperature, and the holding time in the pyrolysis zone itself.

In the book written by Basu, 2010, the different factors that affect pyrolysis products are described. For example, biomass composition affects pyrolysis products due to its molecules composition, hemicellulose, cellulose, and lignin. Each with different initiation temperature for pyrolysis and different decomposition products. Hemicellulose decompose into more non-condensable gas yields and has pyrolysis initiation temperature range of 150-350 °C, cellulose decompose into more condensable vapour and has pyrolysis initiation temperature range of 275-350 °C, while lignin, owing to its aromatic content, produce more char yields compared to cellulose or hemicellulose, and has broader decomposition temperature range of 250-500 °C.

Pyrolysis temperature affects the products of pyrolysis dramatically. Various gases produced at a different ranges of temperature in pyrolysis as shown in the figure below, which describe the dry distillation of wood. We may also see that certain gases start to dominate the products at certain ranges of temperature.

The amount of char produced is also effected by the pyrolysis temperature. Low temperature results in more char while higher temperature produce less. In the figure which describes the pyrolysis of birch wood biomass, it is shown that char product yield decreases over higher temperature. We may also see that larger particles of char also start decreasing on higher temperature.

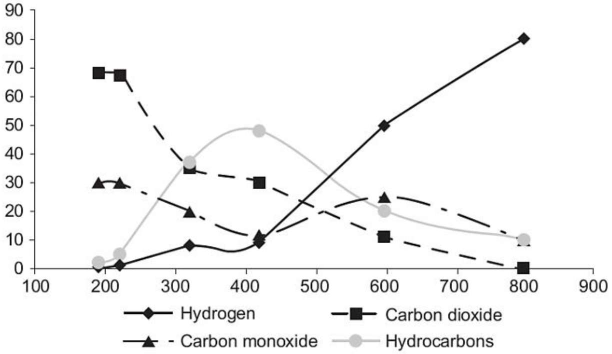


Figure 2.9. Gas releases during dry distillation of wood.

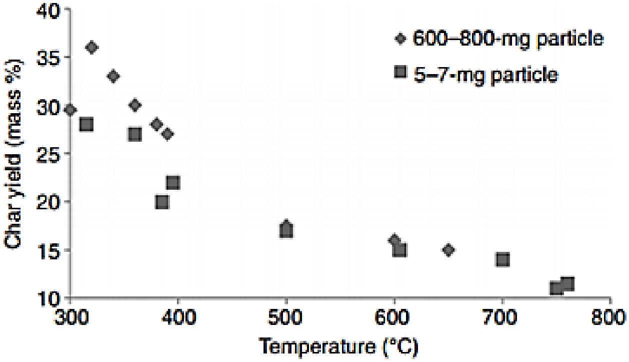


Figure 2.10. Char yield from pyrolysis decreases with increasing temperature

Heating rate is also an important factor in determining the products of pyrolysis. Rapid heating rate to moderate temperature (400-600 °C) yields higher volatiles and liquid, while slower heating rate yields more char. These effects may be simplified into tentative norms summarized as follows:

- Maximizing char yield needs slow heating rate (0.1-2 °C/s), a low pyrolysis temperature, and long gas residence time.
- Maximizing liquid yield needs rapid heating rate, moderate final temperature, and short gas residence time.
- Maximizing gas yield needs slow heating rate, high final temperature, and long residence time.

2.2.5.1.3. Oxidative Pyrolysis Definition

Traditional pyrolysis is performed in a total absence of oxygen. Yet, even in a conventional single stage gasification process, in certain zones, biomass undergoes pyrolysis under a certain oxygen concentration. This phenomenon is called oxidative pyrolysis. This reaction is an exothermal process which produces heat, which in turn will theoretically help the *in situ* temperature of pyrolysis. In multi-stage gasifier, additional air intake is also deliberately added into the pyrolysis zone which also may trigger the oxidative pyrolysis reaction.

In a study performed by Zhao, *et al*, 2014, about oxidative pyrolysis, it was shown that by adding a certain amount of oxygen concentration into the pyrolyzer, the gas and water yield increased, while char yield and tar content reduced as oxygen concentration increased as described in the figure. The higher the oxygen concentration was added, the more distinct the result became.

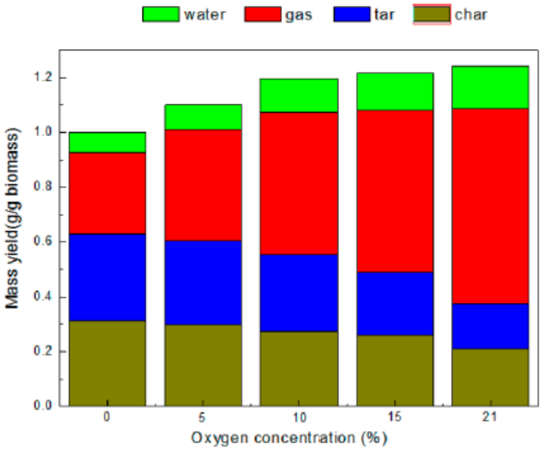


Figure 2.11. Products distribution in an oxidative pyrolysis experiment (Zhao, *et al*, 2014)

In another experiment done by Saleh, *et al*, 2018, about the effect of air ratio and equivalence ratio to gasifier performance using two stage gasifier. Using four kinds of air ratio, 0%, 70%, 80%, and 90% of oxidation air into pyrolysis zone, it was shown that as the air ratio increased, the syngas composition increased as well, due to increased amount of char oxidation, volatiles removal, and drying reaction, triggered by increasing temperature caused by additional heat produced by oxidative pyrolysis reaction. The following figure shows the syngas composition based on the AR variation. When the percentage of AR increases the percentage of gas content and LHV also increased to 4.221 Kj/Kg. The most dominant increase in syngas composition occurs at the pyrolysis stage where the amount of volatile gas (CO, CH_4, CO_2) of oxidative pyrolysis increases from 0.3 g/g of biomass to 0.7 g/g of biomass. H_2 content also increase at oxidative conditions from 0.08 g/g biomass to 0.15 g/g biomass because of the amount of inherent moisture in the fuel entirely converted into water vapor.

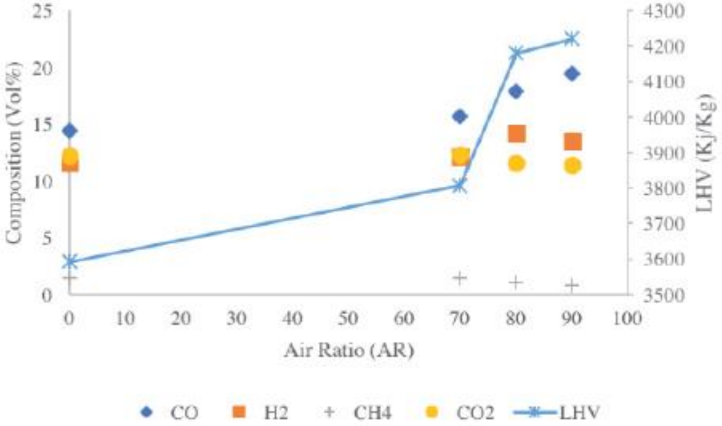


Figure 2.12. Effect of air ratio to Syngas composition

To conclude both research, oxidative pyrolysis causes the balance of reaction to lean towards gas due to increased char oxidation, which will reduce char yield and increase gas composition of products. Oxidative pyrolysis has effects on the biomass itself which could describe the results of aforementioned research. Oxidative pyrolysis causes the outer layer of biomass particle to ignite and form stable ignited layer under its surface. Oxidative condition also reduce organic condensate from the products and increase permanent gases such as CO and CO_2. Heterogeneous oxidation from solid biomass (figure) shows that oxygen diffuses through pores of the particles and absorbed by clusters of functional solid particles. Formation of functional reactive cluster will stimulate the degradation of the biomass particles to release permanent gases and organic condensates (M. Milhe, 2013).

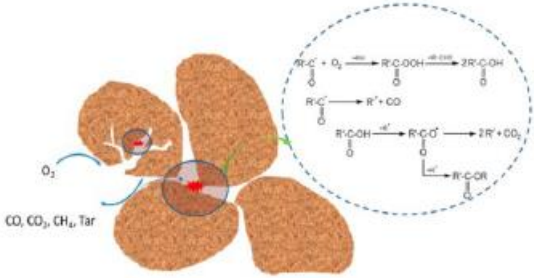
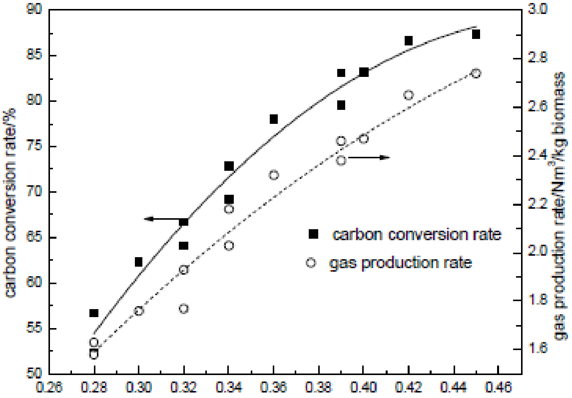


Figure 2.13. Oxidative Pyrolysis within the biomass particle.

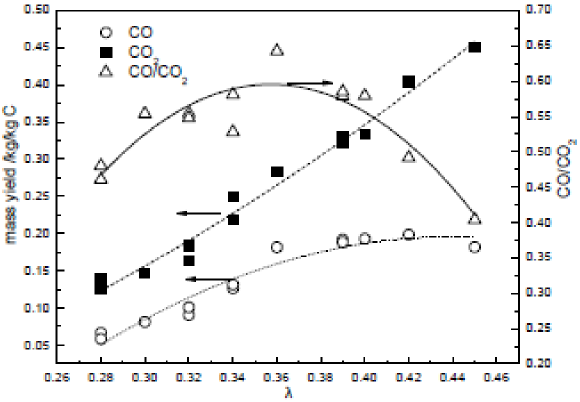
2.2.5.2 Heterogeneous Oxidation

Along with two stage intake gasifier, three stage intake gasifiers were also known to be recently researched. This includes adding additional intake into third zone in the gasifier, namely the reduction zone. H. Shi, *et al*, 2016, conducted experiment using three stage intake gasifier, and the results show that when air is injected into the reduction zone, reactions in the reduction zone occur in an oxidative environment. The injected air will tend to react with carbon compared to gas, since most combustible gases have been consumed in previous zone combustion reaction. This results in increase of gas production rate, as well as carbon conversion rate, since more char reacts with oxidant, forming gases. Yet, as equivalence ratio increases, carbon conversion rate was slightly slowed down, this was due to the fact that as the equivalence ratio increases, more combustion reactions with the already produced syngas occur, increasing temperature, which would cause homogeneous reactions to overwhelm heterogeneous reactions, forming more CO_2 in the product yield, which may be explained in the figure as follows.

Tar reduction becomes the main motivation for researching heterogeneous reaction in reduction zone of gasification. In 2018, Saleh, *et al*, analyse the 3D model of heterogeneous reaction in MSW pellets gasification using multi-stage air intake downdraft gasifier numerically using FLUENT 15 software. Adding air inlet on the reduction zone ranging from 10% to 40%, the simulation results revealed that the addition of a certain amount of air in the reduction zone was able to improve gasification performance in the form of an increase in temperature in the reduction zone and a decrease in temperature in the oxidation, pyrolysis and drying zones which are still above the minimum temperature value, with the best performance parameters achieved in the air ratio of 10%. In addition, there is also an increase in the volumetric gas percentage, especially CO. low heating value and cold gas efficiency also increased, which can be seen in the figure as follows.

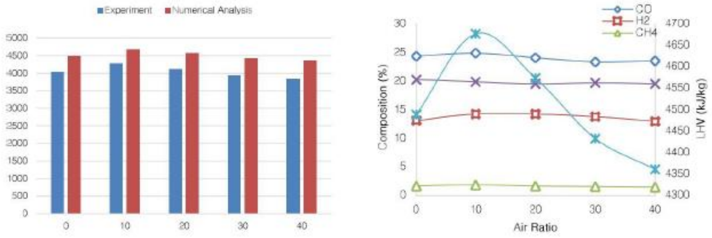


(a)



(b)

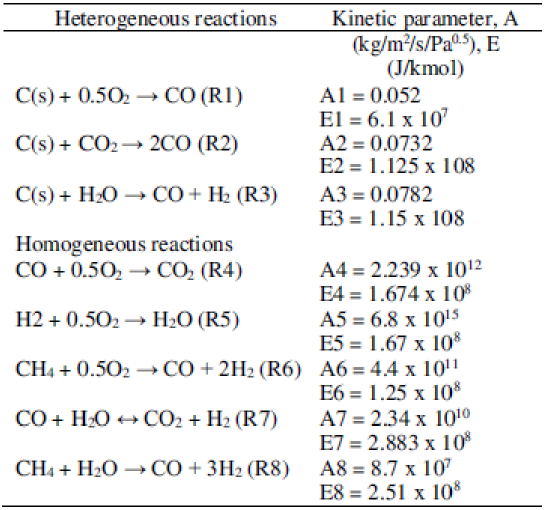
Figure 2.14. (a) Carbon conversion and gas production rate. (b) CO and CO_2 mass yield (H. Shi, *et al*, 2016)



(a) (b)

Figure 2.15. (a) Comparison of LHV from numerical and experimental analysis. (b) Syngas composition and LHV chart at various air ratio.

Table 2.2. Reactions involved in reduction zone (Saleh, *et al*, 2018)



Heterogeneous reactions	Kinetic parameter, A ($kg/m^2/s/Pa^{0.5}$), E (J/kmol)
$C(s) + 0.5O_2 \rightarrow CO$ (R1)	A1 = 0.052 E1 = 6.1×10^7
$C(s) + CO_2 \rightarrow 2CO$ (R2)	A2 = 0.0732 E2 = 1.125 x 108
$C(s) + H_2O \rightarrow CO + H_2$ (R3)	A3 = 0.0782 E3 = 1.15 x 108
Homogeneous reactions	
$CO + 0.5O_2 \rightarrow CO_2$ (R4)	A4 = 2.239×10^{12} E4 = 1.674×10^8
$H2 + 0.5O_2 \rightarrow H_2O$ (R5)	A5 = 6.8×10^{15} E5 = 1.67×10^8
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$ (R6)	A6 = 4.4×10^{11} E6 = 1.25×10^8
$CO + H_2O \leftrightarrow CO_2 + H_2$ (R7)	A7 = 2.34×10^{10} E7 = 2.883×10^8
$CH_4 + H_2O \rightarrow CO + 3H_2$ (R8)	A8 = 8.7×10^7 E8 = 2.51×10^8

Reduction zone involves various homogeneous reactions which is described as the reaction which occurs between reactant in the same state, and heterogeneous reactions which is described as the reaction which occurs between reactant in different states. Additional injection of air change the types of reactions occurring within the reduction zone. The reactions involved in the reduction zone may be described in the table above.

2.2.5.3. Multi Stage and Single Stage Reactions Comparison

2.2.5.3.1 Pyrolysis Zone

Pyrolysis under normal conditions happens in total absence of air. Its reactions consist of thermal decomposition of CC and CO complex (R1, R2, and R3) into CO and CO_2 with a small amount of oxygen coming from the biomass itself. Those reactions may be described as follows.

$$CC_{(f)}(O) = CC_{(f)} + CO \qquad (R1)$$
$$C(O) \,.\, C_{(f)}(O) = CC_{(f)}(O) + CO \qquad (R2)$$

$C(O) . C_{(f)}(O) = CC_{(f)} + CO_2$ (R3)

Meanwhile, in oxidative pyrolysis, there will presumably be an increase in CO and CO_2 gas content, due to increase of oxidant within the zone, related to oxygen diffusion and oxidation of the remaining produced char (R4 and R5). The additional oxidant will also diffuse into the surface of char molecules, stimulating char oxidation reaction, and the increased concentration of CO_2 will also stimulate endothermic reaction akin to *Bouduard* reaction (R6 and R7). These reactions may be described as follows.

$C_{(f)}(O)+1/2O_2 = CC_{(f)} + CO_2$ (R4)
$C. C_{(f)}(O). C_{(f)}(O)+1/2O_2 = CC_{(f)}(O) + CO_2$ (R5)
$2C+1/2O_2 = 2CO$ (R6)
$CO_2 + C = 2CO$ (R7)

The products of biomass devolatilization (CO_2, CO, C_2H_2, H_2O, etc.) will subsequently react with the products of char decomposition and oxidation, producing gases such as H_2O, CO_2, CO, CH_4, H_2, and N_2.

2.2.5.3.2. Reduction Zone

Reduction in normal conditions only occurs between the products of oxidation, which are vapor and CO_2, and pyrolysis, which are char, liquid, and gases. Reaction which occurs between reactants in the same state is called homogeneous reaction, while if it occurs between states it's called heterogeneous reaction. Single stage reduction zone reactions may be described as follows.

$C + CO_2 \leftrightarrow 2CO$ $\Delta H = 172 kJ/mol$
(Boudouard Reaction)

$C + H_2O \leftrightarrow CO + H_2$ $\Delta H = 131 kJ/mol$
(Water Gas Reaction)

$CO + H_2O \leftrightarrow CO_2 + H_2$ ΔH= -41 kJ/mol
(Shift Reaction)

$C + 2H_2 \leftrightarrow CH_4$ ΔH= -75 kJ/mol
(Methanation)

However, as oxidant enters the reduction zone in multi stage gasifiers, balance of reactions will shift towards heterogeneous reactions, since most combustible gases have been used in the previous zone's combustion reactions, which means char-oxygen, water-gas, and *Bouduard* reactions will have an increase in activity, increasing carbon conversion, and gas production rate. However, the remaining syngas from previous processes may also react with the newly injected oxidant, triggering more oxidation reactions which will release more energy. These reactions may be described in the table as follows.

Table 2.3. Multi-stage reduction zone reactions

Reactions	***ΔH* (kJ/mol)**	**Description**
Heterogeneous Reactions		
$C + CO_2 \leftrightarrow 2CO$	+172	Bouduard reaction
$C + H_2O \leftrightarrow CO + H_2$	+131	Water Gas reaction
$C + 0.5O_2 \rightarrow CO$	-111	Char-Oxygen reaction
Homogeneous Reactions		
$CO + 0.5O_2 \rightarrow CO_2$	-284	Complete oxidation
$H_2 + 0.5O_2 \rightarrow H_2O$	-242	Hydrogen combustion
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	-36	Steam reforming reaction (by catalyst)
$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.2	Shift reaction
$CH_4 + H_2O \rightarrow CO + 3H_2$	+206	Steam reforming reaction (by catalyst)

2.2.6 Tar

Tar is commonly perceived as a product of gasification and pyrolysis which can potentially condense, in the colder, downstream component of the unit. In more specific terms, tar is a complex mixture of condensable hydrocarbons, including, oxygen-containing, 1-to-5 ring aromatic, and complex polyaromatic hydrocarbons. Condensed tar has a form of dark, thick, and viscous substance, which, when condensing in low temperature, will stick into components, clog passages in the unit system, which may potentially reduce system overall performance or harm the components or subcomponents of the system.

2.2.6.1. Tar Formation

Tar mainly forms during thermal decomposition of biomass during pyrolysis. Pyrolysis may start at temperature as early as 200 °C, at completes at around 500 °C. During this period, components of biomass, such as cellulose, hemicellulose, and lignin, decompose into primary tar, which contains oxygenates and primary organic condensable components. A literature by Milne, *et al*, 1998, explained that, as the temperature goes up to 500 °C, primary tars begin to rearrange, or in another term, crack, to form more light gases and a series of molecules called secondary tars, which is characterized by phenolics and olefins contents, and continues to reform as temperature increases into further form of tar, called tertiary tars, which contains complex polynucleic aromatic hydrocarbons, which are the most stable form of tar and very difficult to crack without catalyst, as shown in the figure and table below.

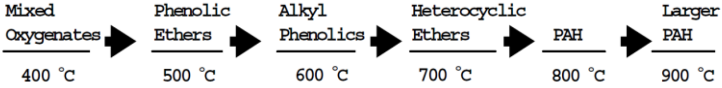
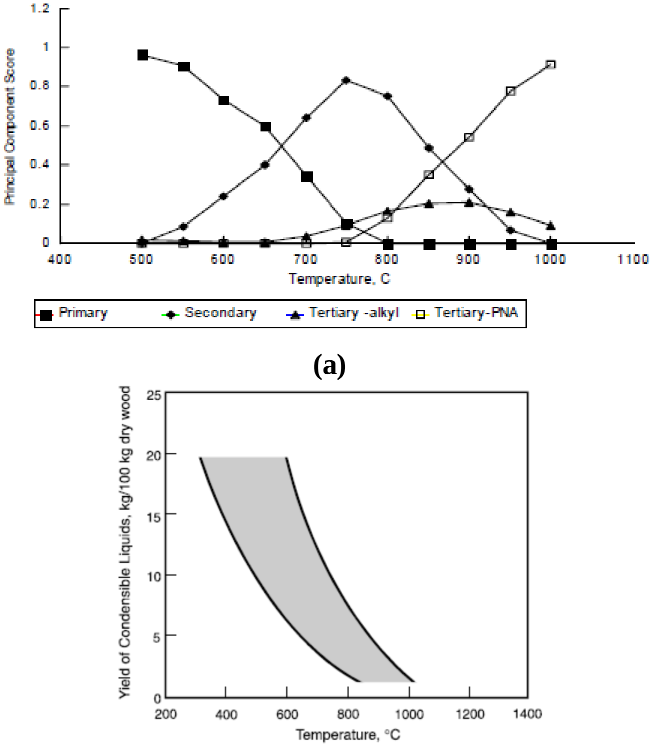


Figure 2.16. Tar maturation chart (Milne, *et al*, 1998)

Table 2.4. Common chemical components in biomass tars (Milne, *et al,* 1998)

Conventional Flash Pyrolysis (450–500 °C)	**High-Temperature Flash Pyrolysis (600–650 °C)**	**Conventional Steam Gasification (700–800 °C)**	**High-Temperature Steam Gasification (900–1000°C)**
Acids Aldehydes Ketones Furans Alcohols Complex Oxygenates Phenols Guaiacols Syringols Complex Phenols	Benzenes Phenols Catechols Naphthalenes Biphenyls Phenanthrenes Benzofurans Benzaldehydes	Naphthalenes Acenaphthylenes Fluorenes Phenanthrenes Benzaldehydes Phenols Naphthofurans Benzanthracenes	Naphthalene* Acenaphthylene Phenanthrene Fluoranthene Pyrene Acephenanthrylene Benzanthracenes Benzopyrenes 226 MW PAHs 276 MW PAHs
			* At the highest severity, naphthalenes such as methyl naphthalene are stripped to simple naphthalene.

As also shown in the figure, tar decomposition, or cracking, depends on the temperature the reactions take place. Other factors which influence tar decomposition include gasification medium, gasification feedstock, residence time, additives and catalysts, also gasifier design. Temperature effects on tar decomposition may be described in the figure as follows.



(a)

(b)

Figure 2.17. (a) Distribution of tars classes as a function of temperature. (b) Tar yield as a function of maximum temperature exposure (Milne, *et al,* 1998)

2.2.6.2. Tar Reduction

Tar reduction can generally be divided into two methods, primary, and secondary methods. Primary methods mean reduction of tar performed from within the gasifier, reducing tar content during its formation. While secondary methods are means of tar reduction after it's being produced, outside the gasifier, through gas cleaning technologies, such as wet scrubbing using particles cyclones, hot gas conditioning, etc.

Currently, studies focus more on primary tar reduction methods, due to its effectiveness, and practicality since it doesn’t require additional components/units in the gasification system. Mainly, primary methods of tar reduction utilize three kinds of reactions, thermal cracking, dry, and steam reforming reactions. Thermal cracking method uses high temperature to decompose tars into more useful substances, and reduce tar contents, as explained in the previous section. Yet, thermal cracking still has some downsides of its own. Since it needs high temperature to operate (~>1000 °C), it may be difficult to achieve such temperature using certain kinds of high moisture biomass, and also, it may produce soot or cause slagging inside the reactor. These reasons drive researchers into studying another methods of tar reduction. Sutton, *et al*, 2001, studied a method of tar reduction using another primary methods of tar reduction, dry and steam reforming using three different catalysts: dolomite, alkali, and nickel reforming catalysts. This method converts unwanted hydrocarbon into syngas using dry (CO_2), steam reforming (H_2O), or both. The reactions may be described as follows.

$$C_nH_m + nH_2O \rightleftharpoons nCO + (n + \frac{m}{2})H_2 \qquad \text{(Steam reforming)}$$

$$C_nH_m + nCO_2 \rightleftharpoons 2CO + (\frac{m}{2})H_2 \qquad \text{(Dry reforming)}$$

The results of the research showed various results for different catalysts. Dolomites increase gas yields at the expense of liquid products. With suitable ratios of biomass feed to oxidant, almost 100% elimination of tars can be achieved. The reforming reaction of tars over dolomite occurs at a higher rate with carbon dioxide than steam Dolomites are not active for reforming the methane present in the product gas and hence they are not suitable catalysts if syngas yield is required.

Alkali catalysts directly added to the biomass by wet impregnation or dry mixing reduce tar content significantly and also reduce the methane content of the product gas. When directly added these catalysts increase the rate of gasification dramatically.

However, the recovery of the catalyst is difficult and costly. Alkali metal catalysts are also active as secondary catalysts. Potassium carbonate supported on alumina is more resistant to carbon deposition although not as active as nickel. The catalyst is not suitable as a secondary catalyst since the hydrocarbon conversion rarely exceeds 80%.

Commercially available nickel reforming catalysts are highly effective at the removal of hydrocarbons and adjustment of the gas composition to syngas quality. The nickel catalysts act best as secondary catalysts located in a downstream reactor, which can be operated under different conditions than those of the gasifier. The catalysts are most active and have longer lifetime when operated at 780 °C in a fluidised-bed. Operated at lower temperatures (600 °C), the catalysts can produce a methane-rich gas. The catalysts are effective, commercially available and relatively cheap.

2.2.7. Gasification Stoichiometry

Gasification process in a gasifier with air intake is inherently an autothermal process, which involves oxidation, in other words, combustion reaction, to provide energy for its remaining reactions. Furthermore, the main reactions of gasification also mostly involve the excess air of oxidation reactions. Which is why, gasification process performance is directly influenced by the stoichiometry of the oxidation reactions.

In stoichiometric conditions, the amount of oxygen needed for biomass oxidation is influenced by the content of the biomass itself. Different biomass has different compositions which influence the balance of oxidation. Which is why, commonly, to determine the stoichiometric amount of air needed for biomass oxidation, ultimate and proximate analysis of biomass is needed to determine the chemical composition of biomass. Then, the stoichiometric amount of air needed to oxidize the biomass can be calculated using following equation (Basu, 2010). Assuming that dry air contains 23.16% oxygen, 76.8% nitrogen, and 0.04% inert gases by weight.

$$M_{da} = [0.1153\,C + 0.3434\,(H - O/8) + 0.0434\,S]\ \mathrm{kg/kg\ dry\ fuel}$$

Yet, stoichiometric amount of oxidation is ideally unnecessary for gasification, since it mainly produces carbon dioxide and risks of slagging and increased ash production. Therefore, generally, gasification process use partial oxidation process to provide its energy. Partial oxidation of gasification ideally use partial oxidation reactions with an equivalence ratio of 0.2-0.4. Equivalence ratio is symbolized by the character lambda (λ). Its definition is given by following equation.

$$\lambda = \frac{\mathrm{AFR}}{\mathrm{AFR_{stoich}}}$$

AFR stands for Air-Fuel Ratio, which means the ratio of the amount of air provided for combustion to the present amount of fuel, which is given by the equation:

$$AFR = \frac{\dot{m}\ air}{\dot{m}\ fuel}$$

2.2.8. Gasification Performance Parameters

Performance parameters are necessary factors to assess a system feasibility and locate its strengths and weaknesses. A gasification process performance is measured through parameters which state the quality and quantity of produced syngas. These parameters measure the composition, quantity, production rate, energy content, energy conversion efficiency, and the tar content of the produced gas.

2.2.8.1 Syngas Composition

Gas composition state the contents of flammable gas in terms of %volume of the syngas. This parameters include the content of CO, CO_2, H_2, and CH_4 inside the syngas, which can be found through ultimate and proximate analysis of the syngas.

2.2.8.2. Syngas Production Rate

This parameter can be directly measured from the gasifier exhaust port, or may be expressed through following equation.

$$\dot{m}_{syngas} = \rho_{gas}\ x\ \frac{Volume_{syngas}}{flow\ time}$$

2.2.8.3. Syngas LHV

LHV of syngas can be calculated by summing the concentration of flammable gas (CO, H_2, and CH_4) contents and their combustion heat, which may be expressed through following equation.

$$LHV = \sum_{i=1}^{n} (\mathrm{Yi}\,.\,LHV\mathrm{i})$$

2.2.8.4 Syngas Cold-Gas Efficiency

Cold-Gas efficiency is defined as the amount of energy in the mass of converted gas products, compared to the total energy in a mass of solid, unprocessed biomass. This roughly translates to the amount of energy transferred into the converted products from its solid biomass origin. This parameter can be expressed as follows.

$$\eta_{cg} = \frac{Q_g M_g}{LHV_f\, M_f}$$

Where LHV_f is the lower heating value of the solid fuel/biomass in MJ/kg, M_f is the mass of the solid fuel/biomass in kg, M_g is the yield of gas product in kg, and Q_g is the LHV of the gas product in MJ/kg.

2.2.8.5. Syngas Tar Content

Tar content within the gas product can be expressed in the following equation.

$$\boldsymbol{Tar\ content = \frac{m_{tar}}{Vsyngas}}$$

Where tar mass is in mg or g, and syngas volume is in Nm^3.

2.3. Previous Researches

2.3.1. Oil Palm Frond Biomass

Sulaiman, *et al*, 2011, studied the temperature profile in gasification of oil palm fronds. The type of gasifier used in this experiment was a 50 kW fixed bed downdraft type using raw oil palm fronds as feedstock. Moisture content values of the OPF was varied to 15%, 20%, and 30%.

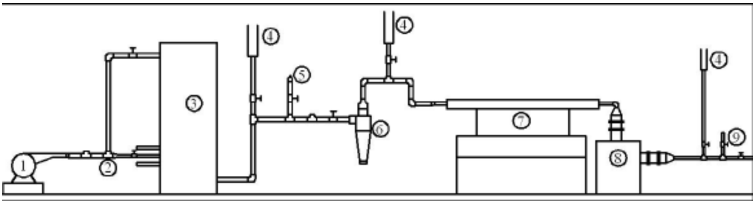


Figure 2.18. Schematic drawing of experimental setup: (1) air blower, (2) air distribution line, (3) downdraft gasifier, (4) gas flare points, (5) raw gas sampling point, (6) cyclone for gas cleaning, (7) cooling heat exchanger, (8) oil bath filter, (9) clean gas sampling point (Sulaiman, *et al,* 2011)

The results showed that stable flare of blue color as able to be obtained at 60% of operation time, indicating that a syngas products high in hydrogen and methane had been achieved. In addition, the study on moisture level effects in gasification temperature profile showed that initial moisture content higher than 15% resulted in a much lower temperature than the acceptable level. Additionally, it was also state that there was no gas flare obtained during the gasification of 20% and 30% moisture content OPF, which concluded that a feedstock with moisture content of 15% or lower was necessary, at least for use in downdraft gasifier. The results are presented in the following figure

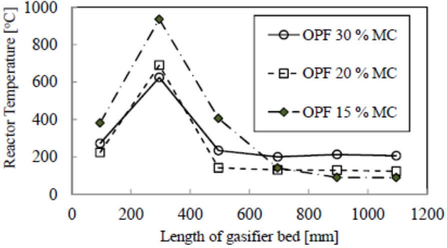


Figure 2.19. Variation of reactor temperature along the gasifier bed for different initial moisture content of OPF (Sulaiman, *et al*, 2014).

2.3.2. Two Stage Gasifiers

Sudarmanta, 2009, studied the effects of combined dual fuel of biodiesel and syngas on engine performance. The gasification process was performed using preheated, two-stage air intake downdraft gasifier with rice seed husk biomass as the feedstock. The purpose of the research was to determine the capability of the syngas to replace diesel fuel as an alternative fuel, in other words, to find how much syngas can substitute the biodiesel, in terms of syngas substitution percentage, before the engine performance drops. The diesel engine was connected to a 3 kWe synchronous generator for loading measurement.

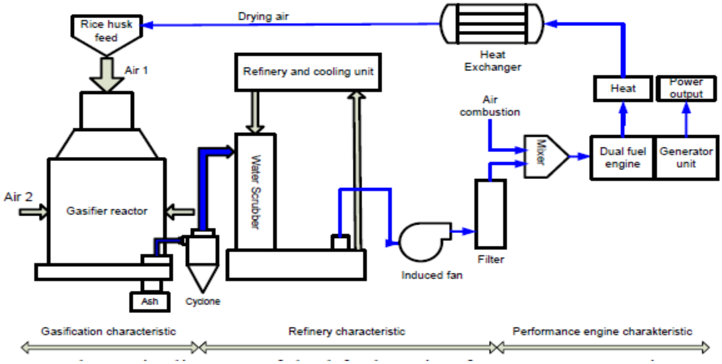


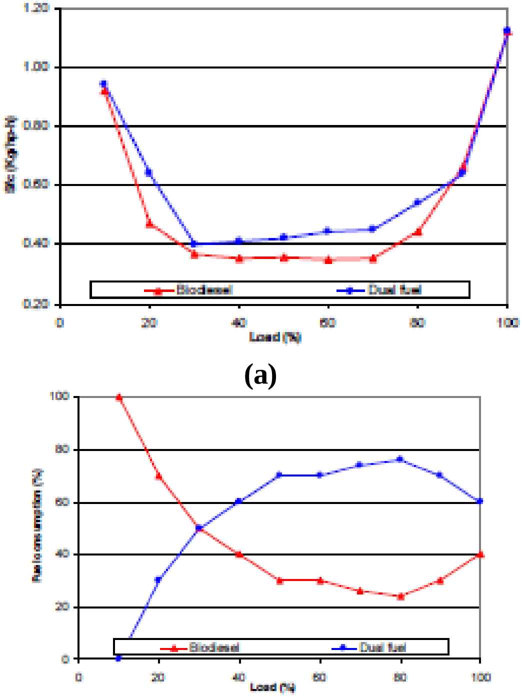
Figure 2.20. Syngas-assisted dual fuel power generation system schematic (Sudarmanta, 2009)

The gasification process performed in this research produced a relatively linear results, with the increase of cold gas efficiency along with the increase of total mass of air into the pyrolysis zone, as seen in the table 2.5. This is presumably due to the increase of char oxidation and devolatilization reactions due to increase of oxidants and the eventual increase in temperature in the pyrolysis region, which would subsequently yield more syngas composition, increasing energy content within the gas products.

Table 2.5. Gasification energy balance (Sudarmanta, 2009)

T	Energy inlet (kJ)				Energy outlet (kJ)				
	Biomass	Air 1	Air 2	Total	Syn-gas	Chart	Ash	Heat transfer	Total
30°	88000.92	806.26	806.26	89613.44	41311.03	22880.24	10.65	986.47	65188.40
40°	88000.92	806.26	809.10	89616.29	42028.52	25520.27	15.24	802.77	68366.80
50°	88000.92	806.26	810.41	89617.59	44644.95	26048.27	26.16	2359.59	73078.98
60°	88000.92	806.26	810.17	89617.36	44136.96	26400.28	40.92	1578.87	72157.02
70°	88000.92	806.26	808.47	89615.66	44001.67	29920.31	63.70	1538.82	75524.51

In terms of substitution performance, using dual-fuel mode increased fuel consumption compared to using 100% biodiesel. This result was quite reasonable, since pure biodiesel has more energy content than syngas-substituted dual fuel, the diesel engine must consume more fuel to maintain its intended performance when using dual fuel. While in terms of substitution percentage, syngas could substitute for up to 60% of total fuel consumption before the engine performance drops, as shown in the following figures.



(a)

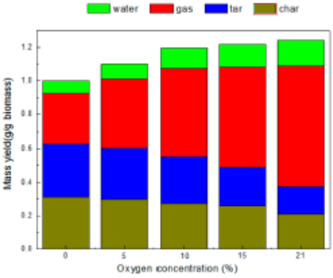
(b)

Figure 2.21. (a) Specific fuel consumption vs engine load. (b) Substitution percentage vs engine load (Sudarmanta, 2009).

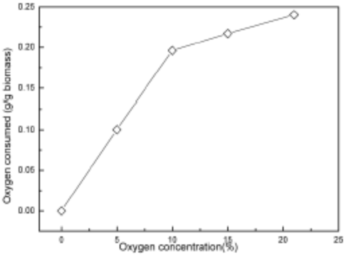
Zhao, *et* al, 2014, studied the effects of oxygen concentration in pinewood sawdust pyrolysis. The research was performed using fixed bed gasifier known as hot rod gasifier using external oven as the heater, utilizing mass flow controller to adjust oxygen concentration and carrier gas flow. The results showed that, with the increase of the oxygen concentration, the char and tar yields decreased, while water and gas increased. The total product mass increased because more oxygen reacted in the oxidative pyrolysis reactions under higher oxygen concentrations.

Due to increased amount of oxidant, the products of pyrolysis showed increasing composition of permanent gases, such as CO, CH_4, and CO_2. This was presumably caused by promoted pyrolysis reactions, in which, as temperature increases, thermal decomposition reaction increased in activity, which will increase pyrolysis products yield such as char and volatiles. Consequently, in the presence of oxidant, with which pyrolysis products would readily react in form of char oxidation or volatiles reactions, permanent gases would form and subsequently increase the products yield.

In terms of tar reduction, oxygen concentration was also proven to show a significant effects. The experiment showed that, as oxygen concentration in the pyrolysis zone increased, the less pyrolysis tar was produced. This may be as a result of the more drastic radical reaction, which will convert primary tar to secondary tar or permanent gases. The results of the experiment can be observed in the following figures.



(a)



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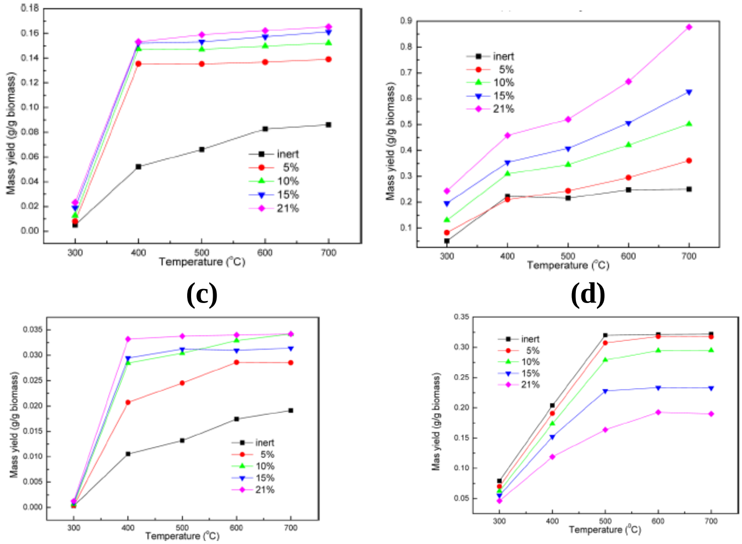


(c) (d)

(e) (f)

Figure 2.22. (a) Products distribution at 500 °C. (b) Oxygen consumption. (c) CO mass yield. (d) CO_2 mass yield. (e) CH_4 mass yield. (f) Tar yield. (Zhao, *et al*, 2014).

Guteres, 2018, studied the effects of additional air intake into the reduction zone on two stage downdraft gasifier using municipal solid waste (MSW) as the feedstock

Table 2.6. Syngas composition (Guteres, 2018).

AR %	Syngas Composition					
	CO (% vol)	H2 (% vol)	CH4 (%vol)	CO2 (% vol)	N2 (% vol)	O2 (% vol)
0	17.58	10.04	1.02	15.67	50.99	4.71
10	18.03	11.10	1.15	15.29	50.79	3.65

20	17.32	11.06	1.01	14.95	50.85	4.82
30	16.64	10.67	0.91	15.12	50.95	5.71
40	16.76	9.93	0.82	14.99	50.89	6.61

Table 2.7. Syngas LHV and cold-gas efficiency (Guteres, 2018).

AR (%)	flammable gas LHV			Syngas LHV (kJ/kg)	MSW LHV (kJ/kg)	Cold Gas Efficiency (%)
	CO (kJ/m3)	H2 (kJ/m3)	CH4 (kJ/m3)			
0	12633	10783	35883	3563	15149	60,53
10	12633	10783	35883	3788	15149	63,93
20	12633	10783	35883	3659	15149	62,47
30	12633	10783	35883	3519	15149	59,46
40	12633	10783	35883	3434	15149	58,04

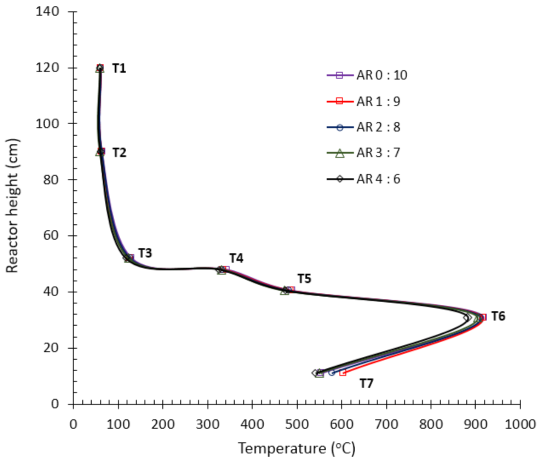


Figure 2.23. Gasifier temperature distribution (Guteres, 2018).

. The injected reduction zone air percentage was adjusted to 0-40% of total air input. The results showed that by injecting certain amount of air into the reduction zone, 10% of total air to be precise, the performance of gasification improved, in terms of flammable gas contents, products LHV, Cold-gas efficiency, and tar content. This is due to the fact that only certain amount of oxygen may be able to react with char to produce energy needed for gasification. In fact, reduction zone temperature reduced on variations after 10% of air ratio. The research also showed that the least excess oxygen was also found in the 10% AR. This proved that the oxidation reaction in reduction zone may need a certain amount of temperature to react properly, which was why excess oxygen increased during later variations. Results of the research can be observed in the preceding figures.

2.3.3. Three Stage Gasifiers

H. Shi, *et al*, 2016, conducted experiment using three stage intake rotary kiln gasifier. The pilot scale gasifier was divided into three different reaction regions, which were oxidative degradation, partial oxidation and char gasification. Optimum gasification equivalence ratios (0.28 to 0.45) were used, and three different air injection percentage (AIP) conditions were tested, which were condition 1 (1:7:2), condition 2 (2:6:2) and condition 3 (3:5:2).

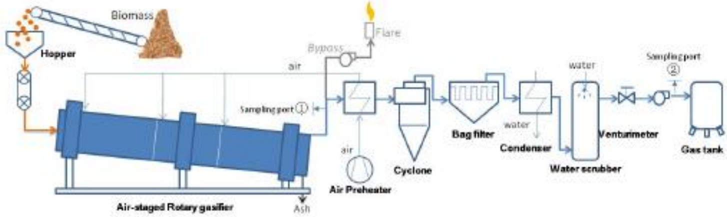


Figure 2.24. Flow diagram of rotary kiln gasifier by H. Shi, *et al*, 2016.

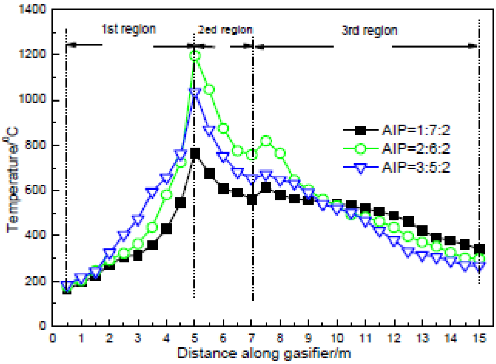
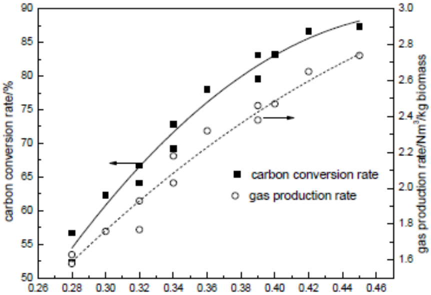


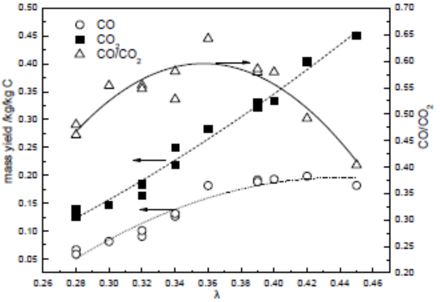
Figure 2.25. Temperature profile variation with conditioned AIP at λ =0.36 (H. Shi, *et al*, 2016)

The results in figure showed that the temperatures of the pyrolysis region (1st region) rose up as the injected air is increased, since more oxygen entered the pyrolysis region, causing more char oxidation reactions to take place. In the second region, oxygen was injected into the gaseous phase, where it mixed with pyrolytic gas and resulted in a homogeneous partial oxidation reaction. Therefore, the environment temperature suddenly increased. In this experiment, although air injection in the second region decreased from 0.7 to 0.6, the peak temperature rose from 765 to 1196 °C. This indicated that more combustible gas was produced under condition 2. Under condition 1, the temperature in the first region was too low for the biomass decomposition reactions to take place. The pyrolytic gas produced was less than under condition 2. Therefore, even though the oxygen injection in the second region was higher; there was not enough gas for combustion, and as a result, the temperature decreased. Under condition 3, the temperature in the second region decreased. Although the pyrolysis reaction was enhanced due to the higher temperature, a large amount of injected oxygen may cause an oxidation of the pyrolytic products in the same time they are produced. In addition, a lack of oxygen in the second region restrains the secondary oxidation of the pyrolytic gas. For these reasons, the temperature in the second region was lower than under condition 2.

In terms of gas yield, the results show that when air is injected into the reduction zone, reactions in the reduction zone occur in an oxidative environment. The injected air will tend to react with carbon compared to gas, since most combustible gases have been consumed in previous zone combustion reaction. This results in increase of gas production rate, as well as carbon conversion rate, since more char reacts with oxidant, forming gases. Yet, as equivalence ratio increases, carbon conversion rate was slightly slowed down, this was due to the fact that as the equivalence ratio increases, more combustion reactions with the already produced syngas occur, increasing temperature, which would cause homogeneous reactions to overwhelm heterogeneous reactions, forming more CO_2 in the product yield, which may be explained in the figure as follows.



(a)



(b)

Figure 2.26. (a) Carbon conversion and gas production rate. (b) CO and CO_2 mass yield (H. Shi, *et al*, 2016).

Ximenes, 2018, performed experiment using MSW biomassusing three stage downdraft gasifier as the equipment. Using air intake ratio of 0 ; 10 ; 0 , 1 ; 6 ; 3, 2 ; 6 ; 2, 3 ; 6 ;1, 1 ; 8 ; 1, 2 ; 7 ; 1, 1 ; 7 ; 2, with each ratio number showing the ratio of air mass flow into pyrolysis:oxidation:reduction zones respectively

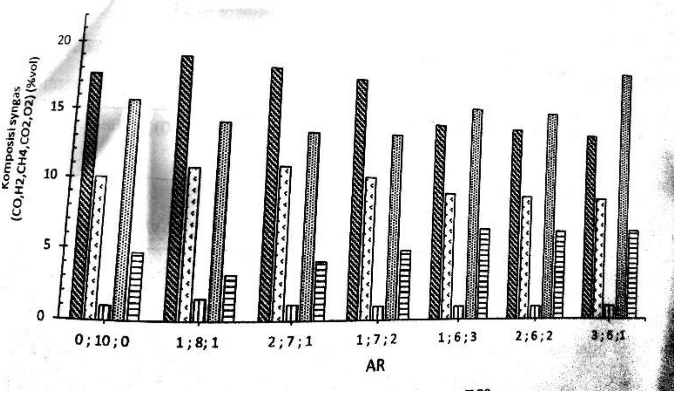


Figure 2.27. Gas composition chart (Ximenes, 2018)

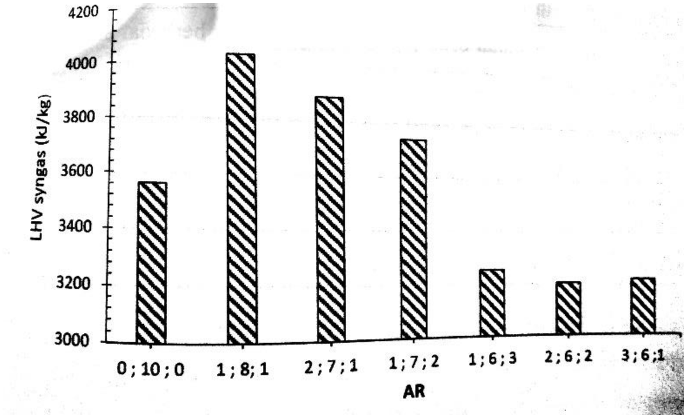


Figure 2.28. Syngas LHV chart (Ximenes, 2018)

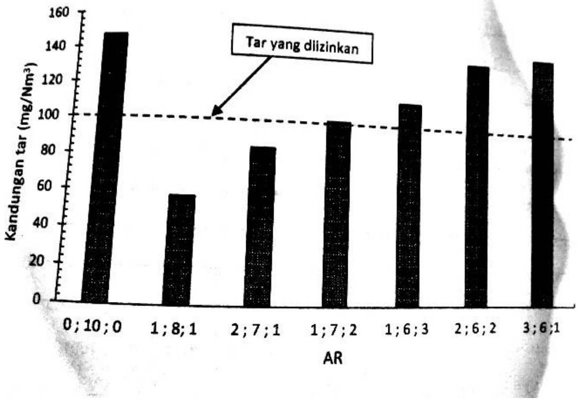


Figure 2.29. Tar content chart (Ximenes, 2018).

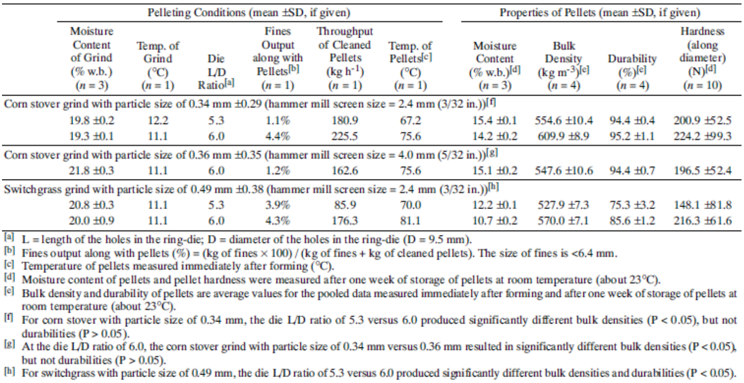
The experiment showed that by increasing the additional amount of air intake into both the pyrolysis and reduction zone to a certain degree, gasification process could be optimized, with the best result acquired at 1: 8: 1. This was shown in his experiment result data, which states that, the LHV and cold-gas efficiency of the resulting syngas increased compared to not injecting additional air into the pyrolysis and reduction zone (0:10:0 ratio), with the increased value being from 3563 kJ/kg to 4034 kJ/kg for LHV and

60,53% to 70% for cold-gas efficiency. The composition of syngas also increased as shown in the chart. The tar content of syngas was also reduced from 146,98 mg/Nm^3 to 57,29 mg/Nm^3.

2.3.4. Biomass Pelletization

Biomass is known for its low bulk density Pelletization is one of the means to ease and simplify the process of biomass transport, storage, and use. Kaliyan, *et al*, 2009, studied the effects of biomass pelletization and briquetting using corn stover and switchgrass biomass as the research material.

Table 2.8. The properties of resulting corn stover and switchgrass pellets



	Pelleting Conditions (mean ±SD, if given)						Properties of Pellets (mean ±SD, if given)			
	Moisture Content of Grind (% w.b.) ($n = 3$)	Temp. of Grind (°C) ($n = 1$)	Die L/D Ratio[a]	Fines Output along with Pellets[b] ($n = 1$)	Throughput of Cleaned Pellets (kg h^{-1}) ($n = 1$)	Temp. of Pellets[c] (°C) ($n = 1$)	Moisture Content (% w.b.)[d] ($n = 3$)	Bulk Density (kg m^{-3})[e] ($n = 4$)	Durability (%)[e] ($n = 4$)	Hardness (along diameter) (N)[d] ($n = 10$)
Corn stover grind with particle size of 0.34 mm ±0.29 (hammer mill screen size = 2.4 mm (3/32 in.))[f]										
	19.8 ±0.2	12.2	5.3	1.1%	180.9	67.2	15.4 ±0.1	554.6 ±10.4	94.4 ±0.4	200.9 ±52.5
	19.3 ±0.1	11.1	6.0	4.4%	225.5	75.6	14.2 ±0.2	609.9 ±8.9	95.2 ±1.1	224.2 ±99.3
Corn stover grind with particle size of 0.36 mm ±0.35 (hammer mill screen size = 4.0 mm (5/32 in.))[g]										
	21.8 ±0.3	11.1	6.0	1.2%	162.6	75.6	15.1 ±0.2	547.6 ±10.6	94.4 ±0.7	196.5 ±52.4
Switchgrass grind with particle size of 0.49 mm ±0.38 (hammer mill screen size = 2.4 mm (3/32 in.))[h]										
	20.8 ±0.3	11.1	5.3	3.9%	85.9	70.0	12.2 ±0.1	527.9 ±7.3	75.3 ±3.2	148.1 ±81.8
	20.0 ±0.9	11.1	6.0	4.3%	176.3	81.1	10.7 ±0.2	570.0 ±7.1	85.6 ±1.2	216.3 ±61.6

[a] L = length of the holes in the ring-die; D = diameter of the holes in the ring-die (D = 9.5 mm).

[b] Fines output along with pellets (%) = (kg of fines × 100) / (kg of fines + kg of cleaned pellets). The size of fines is <6.4 mm.

[c] Temperature of pellets measured immediately after forming (°C).

[d] Moisture content of pellets and pellet hardness were measured after one week of storage of pellets at room temperature (about 23°C).

[e] Bulk density and durability of pellets are average values for the pooled data measured immediately after forming and after one week of storage of pellets at room temperature (about 23°C).

[f] For corn stover with particle size of 0.34 mm, the die L/D ratio of 5.3 versus 6.0 produced significantly different bulk densities ($P < 0.05$), but not durabilities ($P > 0.05$).

[g] At the die L/D ratio of 6.0, the corn stover grind with particle size of 0.34 mm versus 0.36 mm resulted in significantly different bulk densities ($P < 0.05$), but not durabilities ($P > 0.05$).

[h] For switchgrass with particle size of 0.49 mm, the die L/D ratio of 5.3 versus 6.0 produced significantly different bulk densities and durabilities ($P < 0.05$).

Using pilot-scale ring-die pelleting machine, the results showed that, from initial bulk density of biomass bales ranging from 100-200 kg/m^3, pelletization could increase the biomass bulk density, with around 548-610 kg/m^3 for corn stover, and around 528-570 kg/m^3 for switchgrass biomass. This proved that pelletization could produce biomass better in quality and convenience, compared to its bulk counterparts.

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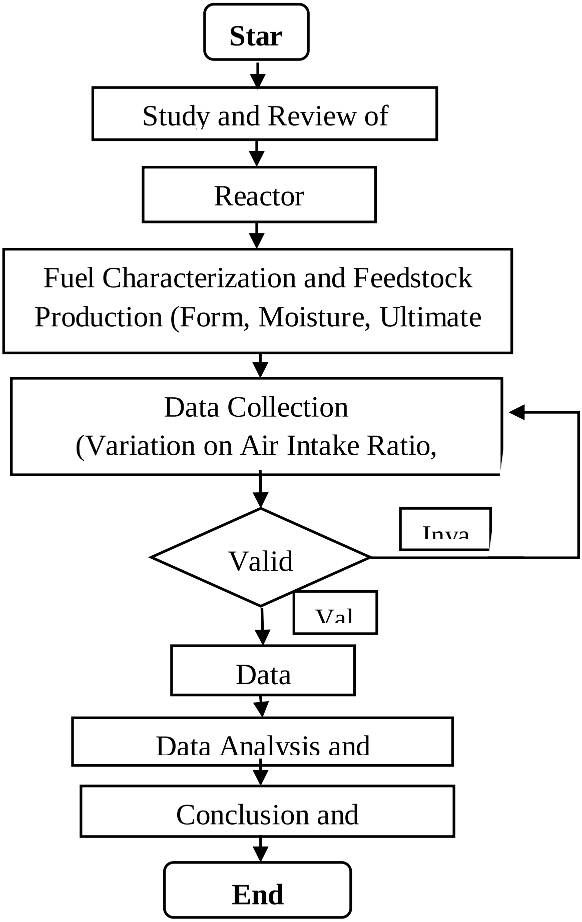
CHAPTER III
RESEARCH METHODOLOGY

3.1. Research Design and Flow Chart



Based on the research flowchart depicted above, the study and research itself will be performed experimentally within the laboratory. The research will be performed subsequently within the procedure as follows:

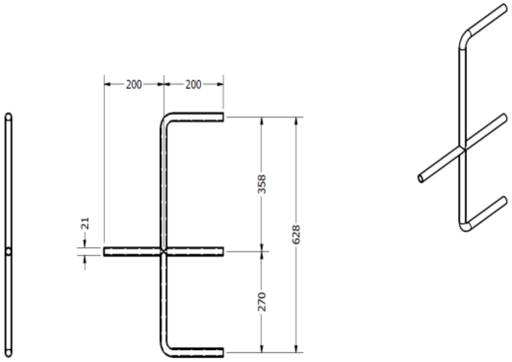
3.1.1. Review and Study of Literatures

Research starts with the study and review of related literatures. Literatures studied including journals, theses, and books related to gasification theory, multi-stage air intake theory and experiments, primary tar reduction methods, downdraft gasifier theory and experiments, and oil palm fronds (OPF) gasification theory and experiments.

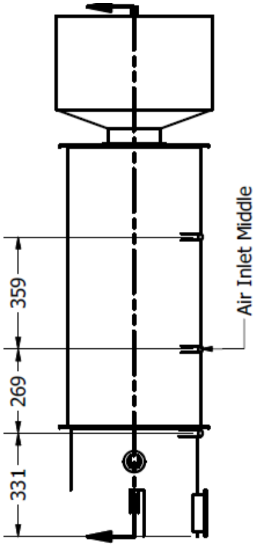
3.1.2. Reactor Modification

Modifications are done on the downdraft gasifier owned by ITS Mechanical Engineering Department Laboratory of Fuel and Combustion Engineering. Modifications performed were mainly in the form of additional air intake passages added into the pyrolysis and reduction zone along with imperative oxidation air intake, effectively making the reactor a three staged air intake gasifier. This method is expected to increase the performance of gasification process by increasing the quality of syngas yield, syngas LHV (>45 MJ/Nm^3), Cold-Gas Efficiency (>70%), and reducing syngas tar content (<100 mg/Nm^3) (Milne, *et al,* 1998).

(a)



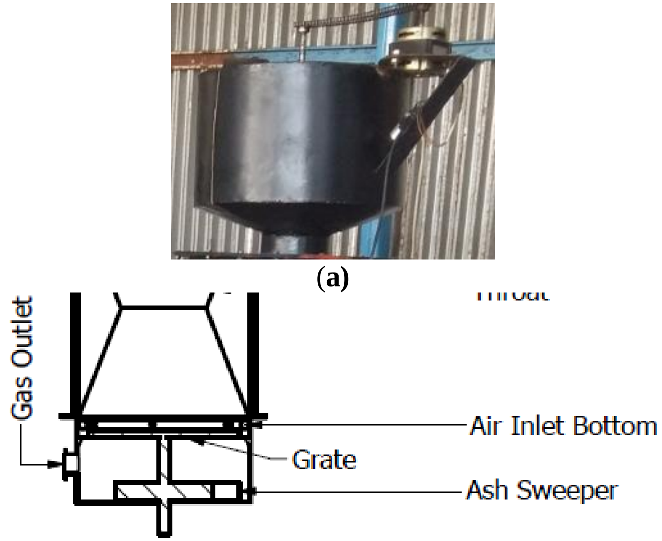
(b)



(c)

Figure 3.1. (a) Three Stage Air Intake pipeline. (b) Three Stage Air Intake scheme. (c) Three Stage Air Intake positioning along the gasifier.

Modifications are also added in form of additional complementary components, which are hopper and bottom ash sweeper. Hopper is used to perform continuous operation in gasifier, while ash sweeper is used to clean ash buildup in the bottom of the gasifier to ensure optimal operation of gasifier.



(a)

(b)

Figure 3.2 (a) Hopper, and (b) Ash Sweeper.

3.1.3. Biomass Characteristics

The type of biomass used in this research is oil palm fronds (OPF). Palm fronds must first be chopped to pieces, then shredded into shreds about 2 mm in size. OPF shreds are then dried under the sun for around 16 hours to reduce their moisture. Afterwards, OPF shreds are moisturized with the water and then pelletized to produce OPF pellets about 6x10 mm in size.

3.1.4. Data Presentation, Analysis, and Interpretation

Data analysis and interpretation are also performed in the research to process the collected data, interpret its behavior, and find any possible error and uncompleted data in data collection. Data which is going to undergo analysis and interpretation are temperature distribution, syngas LHV and composition, syngas yield rate, and tar content.

3.1.5. Research Conclusion and Recommendation

Research conclusion and recommendation explain the result of the research, its relation to initial aim, proving or disproving hypotheses, and give constructive advices and critics about any drawbacks or flaws within the research to improve similar research to be done in the future.

3,2, Instruments and Materials

3.2.1. Instruments Configuration Scheme

Instruments configuration can be seen in figure 3.

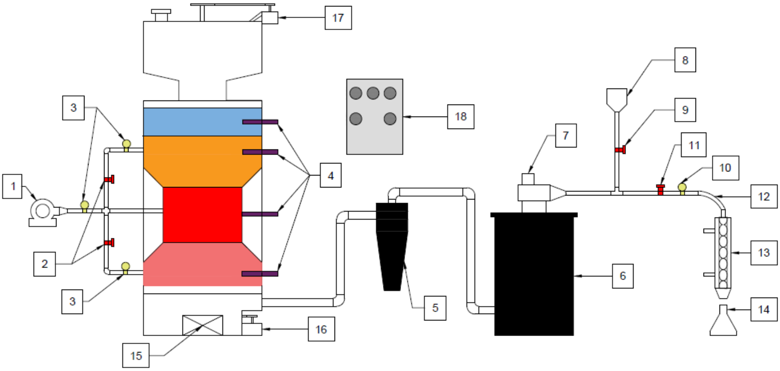


Figure 3.3. Instruments configuration.

Description:

1. Force draft fan
2. Inlet valves
3. Pitot tubes
4. Thermocouples
5. Cyclone
6. Dry filter
7. Induced draft Fan
8. Flare stack
9. Stack valve
10. Pitot tube
11. Syngas valve
12. Sample tube
13. Tar sampling set
14. Tar container
15. Ash box
16. Ash sweeper motor
17. Hopper motor
18. Control Panel and Temperature logger

3.2.2. Measuring Instruments

1. Temperature Measurement

Temperature measurement uses 4 K-type thermocouples installed inside the reactors in various points shown in the figure to determine the temperatures of gasification zones.

Figure 3.4. Type k thermocouple with long probe

2. Mass Flow Measurement

Fluid mass flow measurement is done through pre-installed pitot tube on pipe passages. Final measurement can be calculated from pressure difference (δp) which could be measured from digital manometer. The calculation is provided as follows.

- Calculating maximum flow speed (Vmax)

$$V1 = \sqrt{\frac{2(Po - Pi)}{\rho air}}$$

With :

Po-Pi = Manometer measurement (Pa)

ρ_{air} = Air density (1.1644 kg/m^3 at 30 °C)

- Calculating Reynold number at vmax (Re_{vmax}) value

$$Re_{vmax} = \frac{\rho_{air}.V_{max}.D}{\mu}$$

With:

D = Pipe diameter (m)

μ = Air viscosity at 25 °C (184.6 x 10^{-7} kg/(m.s))

- Calculating n value (variation of power law exponent)

n = -1.7 + 1.8 log Re_{vmax}

- Calculating average flow speed ($\bar{V}$)

$$\frac{\bar{V}}{V_{max}} = \frac{2n^2}{(n+1)(2n+1)}$$

- Calculating air mass flow

$$\dot{m}_{air} = \rho_{air}.\bar{V}.A_{pipe}$$

Pitot tubes are placed on two points. First, intake pipes to measure inlet mass flow. And second, on syngas outlet pipe, to measure syngas yield. The flow readings passing through these instruments may then be read through a digital manometer.

Figure 3.5 Digital Manometer

3. Gas *Chromatography*

Gas chromatography is used to measure the volumetric percentage of syngas composition such as CO, CO_2, H_2, and CH_4.

Figure 3.6. Gas Chromatography instrument

Measurement is performed in the Material and Energy Chemistry Laboratory (Lab KME, Kimia, ITS).

3.2.3. Materials

Biomass used in this research is oil palm fronds (OPF) pellets. Pelletized form is used due to its higher density and lower moisture content. First, before use, biomass will undergo proximate and ultimate analysis for further calculation in research, for example, ER calculation, Cold gas efficiency, etc. Before pelletizing, raw OPF must be shredded for ease of operation. OPF pellets must be manually dried out afterwards under the sun for around 3 days before use. Pellets have average dimensions of around 6 mm in diameter and 5-15 mm in length.

Figure 3.7. Ultimate and Proximate Analysis Instruments.

Figure 3.8 OPF pellets dried out in the sun.

Table 3.1. Oil Palm Fronds biomass properties (LPPM, ITS)

Parameters	Value
Ultimate Analysis (%)	
• Carbon	44.58
• Hydrogen	4.53
• Nitrogen	0.71
• Sulphur	0.07
• Oxygen	48.80
• HHV (MJ/kg)	17.28
Proximate Analysis (%)	
• Ash	4.50
• Volatile Matter	79.34
• Fixed Carbon	8.36
• Moisture	7.8

3.3. Data Collection Method

3.3.1. Operating Procedure

a. Perform a thorough check on gasification instruments operability, from the gasifier itself to its supporting components such as ash sweeper motor, feeder motor, thermocouple logging panel, inlet and exhaust blower fans. Search for any malfunction in the devices.
b. Connect the temperature data logger to a computer and check for any malfunction in temperature measurement through the data log.
c. Perform a leak check along the piping joints and passages around the gasifier by using blower fans. Check for potential leaks using soap water.
d. Unscrew the base of the fuel hopper and take it off. Doing so will expose the gasifier fuel tank feeding mouth.
e. Fill the fuel tank with biomass fuel through the mouth up to the height of ignition passage tip.
f. Reinstall the fuel hopper on the gasifier and fill it with biomass through the fuel cap above the hopper.

g. Turn on the exhaust blower and ignite the fuel through the ignition passage on the side of the gasifier. Make sure the fuel is ignited by peeking through the passage and look for ignited embers.
h. Turn on the inlet blower and adjust the air intake as needed using the oxidation zone inlet valve.
i. Observe the temperature of the oxidation zone, once the temperature reaches 500 °C, turn on the biomass hopper motor and fill the gasifier tank with biomass as much as necessary.
j. Observe the flammability and the temperature of oxidation zone. Test syngas flammability by igniting the syngas from the flare stack. Once the syngas becomes flammable, and the temperature of oxidation zone becomes steady, start data collection.
k. Sample gas is taken every 5 minutes for every AR variation. Sample gas can only be taken when the syngas has become flammable, and the oxidation temperature steadies. Gas sample is taken from the end of tar condensation set passage, to avoid tar content in the gas sample, and contained in a gas pocket to be analysed later using Gas Chromatography in Material and Energy Chemistry Lab, ITS.

Syngas volume is measured by calculating syngas flowrate using the flow speed reading times the cross sectional area of the pipe, which is then used to calculate flowrate for a given time, in this case 5 minutes.

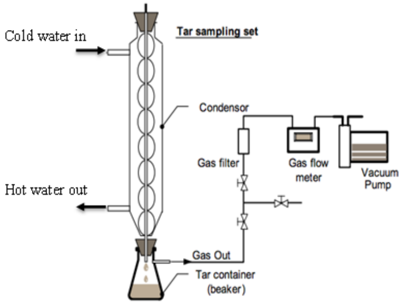


Figure 3.9. Tar sampling set (Guterres, 2018).

The mass of tar is acquired through condensing tar using tar condensing set. This equipment works as a heat exchanger which exchanges heat between cooling liquid, with a temperature of 5-15 °C, and the entering high temperature fluid, in this case syngas, which will subsequently lower its temperature. The temperature decrease will condense tar content inside the syngas, separating them from each other. Liquid tar will flow downward into the beaker glass, allowing its mass to be weighed, but only after letting its water content dry out, which needs approximately 1 hour of heating in a drying oven (Gafur, 2018).

Tar content can then be calculated using the following equation.

$$Tar\ content = \frac{m_{tar}}{V_{syngas}}$$

Where m_{tar} is the mass of weighed tar and V_{syngas} is the measured volume of flowing syngas for a given time.

3.3.2. Operating Conditions

There are 12 different intake air amount variations to test in this experiment. All of them are tested in the condition of equivalence ratio, ER of 0,4. Intake air is varied using gate valves installed to each inlet passages. The amount of air flowing into each passages is measured through the manometer, which will be used as a reference for the variations.

The variations will be stated in the term AR, which stands for air ratio. This shows the ratio of the amount of air going into each zones. In this experiment there will be 12 variations in air intake ratio. Stated in the order of pyrolysis ; oxidation ; reduction AR: 0 ; 10 ; 0 , 1 ; 8 ; 1, 2 ; 7 ; 1, 1 ; 7 ; 2, 1 ; 6 ; 3, 2 ; 6 ; 2, 3 ; 6 ;1, 2 ; 5 ; 3, and 3 ; 5 ; 2.

For example, 1 ; 7 ; 2 variation means 10% of total air mass would flow into pyrolysis zone, 70% into oxidation zone, and 20% into reduction zone, and so on.

Table 3.2 Operating Conditions

AR	ER	Input Mass				
		OPF Feedstock Mass Flow (kg/h)	Air Intake Mass Flow (kg/h)			
			Pyrolysis	Oxidation	Reduction	Total
0 ; 10 ; 0	0.4	5	0	12,704	0	12,704
1 ; 8 ; 1			1,2704	10,1632	1,2704	12,704
2 ; 7 ; 1			2,5408	8,8928	1,2704	12,704
1 ; 7 ; 2			1,2704	8,8928	2,5408	12,704
1 ; 6 ; 3			1,2704	7,6224	3,8112	12,704
2 ; 6 ; 2			2,5408	7,6224	2,5408	12,704
3 ; 6 ;1			3,8112	7,6224	1,2704	12,704
2 ; 5 ; 3			2,5408	6,352	3,8112	12,704
3 ; 5 ; 2			3,8112	6,352	2,5408	12,704

3.3.3. Measuring Parameters

The input and output measuring parameters can be seen in the table below.

Table 3.3. Measuring parameters

Input Parameters		**Output Parameters**	
Constant Variables	**Control Variables**	**Measured Variables**	**Calculated Variables**
- Reactor dimension (h=1,2 m and d=0,254 m) - T $_{\text{surrounding air}}$ - Biomass (type, size, amount, moisture)	- Air intake ratio of pyrolysis, oxidation, and reduction, measured in 10 data variations: a. 0 : 10 : 0 b. 1 : 8 : 1 c. 1 : 7 : 2 d. 2 : 7 : 1 e. 1 : 6 : 3 f. 2 : 6 : 2 g. 3 : 6 : 1 h. 2 : 5 : 3 i. 3 : 5 : 2	- Total biomass consumption duration (s) - $v_{\text{air pyrolysis}}$ (m/s) - $v_{\text{air oxidation}}$ (m/s) - $v_{\text{air reduction}}$ (m/s) - $v_{\text{gas output}}$ (m/s) - T $_{\text{Drying}}$ (^{0}C) - T $_{\text{Pyrolysis}}$ (^{0}C) - T $_{\text{Oxidation}}$ (^{0}C) - T $_{\text{Reduction}}$ (^{0}C) - m_{tar} (mg) - Syngas composition (CO,H_2, CH_4, CO_2,)	- $\dot{m}$ biomass (kg/s) - $\dot{m}$ air (kg/s) - $\dot{m}$ syngas (kg/s) - Syngas LHV - Cold gas efficiency (%) - Tar content (mg/Nm3)

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CHAPTER IV

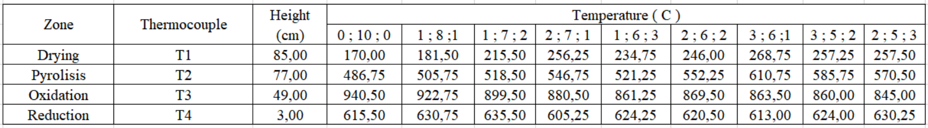
DATA PRESENTATION, ANALYSIS, AND INTERPRETATION

Operational performance of a gasifier to produce flammable gas may be measured through several parameters, such as, syngas composition, production rate, LHV, Cold-Gas Efficiency, and the tar content of resulting syngas.

4.1. Temperature Distribution

Although not included in the main focus in this research, temperature distribution data may become a very good indicator of processes happening along the zones of gasifier (drying, pyrolysis, oxidation, and reduction). Temperature distribution is displayed to find the effects of air intake ratio variations done to the gasification process, which consists of 9 variations: 0 ; 10 ; 0 **,** 1 ; 8 ; 1**,** 2 ; 7 ; 1**,** 1 ; 7 ; 2, 1 ; 6 ; 3**,** 2 ; 6 ; 2**,** 3 ; 6 ;1**,** 2 ; 5 ; 3**,** and 3 ; 5 ; 2**.**

Table 4.1. Temperature distribution data.



Zone	Thermocouple	Height (cm)	Temperature (C)								
			0 ; 10 ; 0	1 ; 8 ;1	1 ; 7 ; 2	2 ; 7 ; 1	1 ; 6 ; 3	2 ; 6 ; 2	3 ; 6 ;1	3 ; 5 ; 2	2 ; 5 ; 3
Drying	T1	85,00	170,00	181,50	215,50	256,25	234,75	246,00	268,75	257,25	257,50
Pyrolisis	T2	77,00	486,75	505,75	518,50	546,75	521,25	552,25	610,75	585,75	570,50
Oxidation	T3	49,00	940,50	922,75	899,50	880,50	861,25	869,50	863,50	860,00	845,00
Reduction	T4	3,00	615,50	630,75	635,50	605,25	624,25	620,50	613,00	624,00	630,25

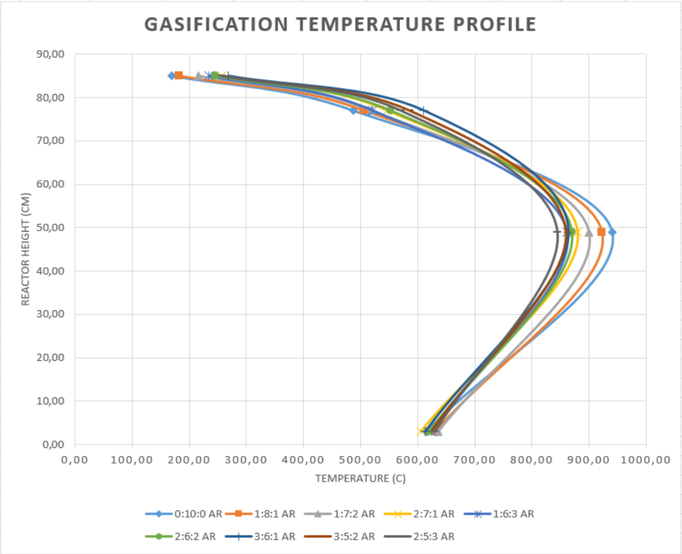


Figure 4.1 Temperature profile chart.

Table 4.1 shows that thermocouple 1 (T1) is placed within the drying zone, since it shows the temperature reading interval between 170 – 268,75 °C, which is close to what was suggested in the reference, which was around 150 °C (Molino,2015), with highest temperature achieved in 3:6:1 variation, which is 268,75 °C. In this zone, the removal of biomass moisture occurs, as the zone is named. This zone has the lowest temperature range, due to its position which is the furthest zone from oxidation zone, which provides the main heat for its endothermic evaporation process. Yet, this zone has a relatively high temperature, rather far above the evaporation temperature of water (moisture), around 100 °C. This is possibly due to the thermocouple placement which is relatively close to the pyrolysis zone which causes the heat from pyrolysis zone to transfer into the drying zone.

T2 reading falls within the pyrolysis zone, since it shows the temperature reading interval between 486,75 – 610,75 °C, which is around the suggested temperature according to reference, which is between 250 – 700 °C (Molino, 2015), with highest temperature achieved in 3:6:1 variation, which is 610,75 °C. During experiment, significant temperature change was observed between variations, as seen in table and figure 4.1. Especially, during 3;6;1 AR variation, it can be seen that there is a sudden significant increase in temperature when additional air is increased. This is caused by exothermic oxidative pyrolysis reaction which occurs when air is introduced into the pyrolysis zone, which provides additional heat to the pyrolysis zone. The additional heat is proven to be advantageous for thermal decomposition and tar cracking process, as seen in previous researches mentioned in the previous chapter. The amount of heat produced also depends on the amount of air introduced into the zone. As seen from the table, temperature increases when more air is injected into the pyrolysis zone, and drops when the air is reduced. The precise amount of air is needed to obtain the optimal products. Optimal amount of air will help to increase syngas quantity by producing additional CO, product of partial oxidation in oxidative pyrolysis reaction, and help thermal decomposition and devolatilization reactions. Too much air and excessive oxidative reactions will occur, and may subsequently overwhelm the original pyrolysis' thermal decomposition reactions, which will only produce combustion products, such as H_2O, CO_2, etc. and diminish the amount of actually useful products of pyrolysis.

On the other hand, T3 shows the highest temperature range compared to other zones, which is 845 – 940,50 °C, with highest temperature achieved in 0:10:0 variation, which is 940,50 °C This shows that T3 is placed within the oxidation zone, which provides exothermic heat to use in another zones. As mentioned in the literature, oxidation is an exothermic process which requires O_2 to occur. Which is why, the rate of this reaction heavily depends on the supply of air. In the table 4.1, it can be seen that the temperature of the reduction zone drops as the amount of injected air introduced into oxidation zone is reduced. This drop of temperature is caused by the decrease of oxidation reactions activity occurring within the oxidation zone.

T4 shows range of temperature between 605,25 – 635,50 °C. This means T4 lies within the reduction zone, which has the temperature range of 500-1600 °C (Molino, 2015). This zone becomes the main process for syngas formation. The main process for reduction zone are:

$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = 172 \text{kJ/mol}$
(Boudouard Reaction)

$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = 131 \text{kJ/mol}$
(Water Gas Reaction)

$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41 \text{ kJ/mol}$
(Shift Reaction)

$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H = -75 \text{ kJ/mol}$
(Methanation)

Temperature within the reduction zone varies with the amount of air injected. The highest temperature achieved in 1:7:2 variation, which is 635,50 °C. As the air ratio is varied, the temperature of reduction zone follows accordingly. This is caused by heterogeneous oxidation reaction occurring in reduction zone between induced air and formed solid char, whose reaction is described as:

$$C+1/2O_2 \quad CO$$

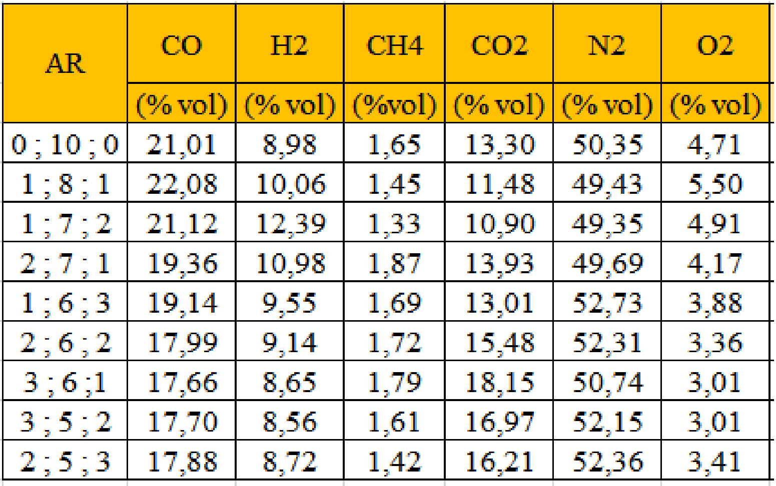
This reaction, similar to oxidative pyrolysis reaction, is an exothermic reaction. This reaction provides additional heat into the reduction zone, which in turn raises temperature. But this reaction also depends on the amount of reactants available within the reduction zone, which are char and oxygen. Oxygen is provided by additional air introduced into the reduction zone, while char can only be obtained while competing with other processes in gasification which also use char. This is why the change of temperature occurring in reduction zone varies between air ratio variations. For example, in variation 1:6:3 and 2:5:3, the same amount of air is introduced into the reduction zone which is 30% of total air. Yet, the temperature data still reads lower than that of 1:7:2 variation. This temperature data may reflect other performance parameter of gasifier which will be observed in the following sub chapters.

Compared to previous researches, for example Ximenes, 2018, this research shows higher temperature, since the material used in this research has higher heating value of 15731,12 kj/kg, compared to Ximenes' research of 15149 kj/kg. Gasification temperature in this research could reach 940,50 °C, while Ximenes' research reached up to 926 °C. This may prove to be favorable, especially for thermal cracking reactions, since thermal cracking reactions need high temperature to occur. The temperature distribution data may reflect other performance parameters, which will be discussed in further sub-chapters.

4.2. Syngas Composition

Another important gasification performance parameter, and one of the focus of this research, is syngas composition. Generally syngas consists of two chemical components, flammable and non-flammable components. Flammable components consist of CO, H_2, and CH_4, while non-flammable components mainly consist of CO_2, N_2, and O_2. These components are categorized based on their heating value. Flammable components have heating value, while non-flammable ones don’t. Table and figure 4.2 shows the volumetric percentage of chemical components contained within the resulting syngas.

Table 4.2 Resulting syngas composition. (Material and Energy Lab, ITS)



AR	CO	H2	CH4	CO2	N2	O2
	(% vol)	(% vol)	(%vol)	(% vol)	(% vol)	(% vol)
0 ; 10 ; 0	21,01	8,98	1,65	13,30	50,35	4,71
1 ; 8 ; 1	22,08	10,06	1,45	11,48	49,43	5,50
1 ; 7 ; 2	21,12	12,39	1,33	10,90	49,35	4,91
2 ; 7 ; 1	19,36	10,98	1,87	13,93	49,69	4,17
1 ; 6 ; 3	19,14	9,55	1,69	13,01	52,73	3,88
2 ; 6 ; 2	17,99	9,14	1,72	15,48	52,31	3,36
3 ; 6 ;1	17,66	8,65	1,79	18,15	50,74	3,01
3 ; 5 ; 2	17,70	8,56	1,61	16,97	52,15	3,01
2 ; 5 ; 3	17,88	8,72	1,42	16,21	52,36	3,41

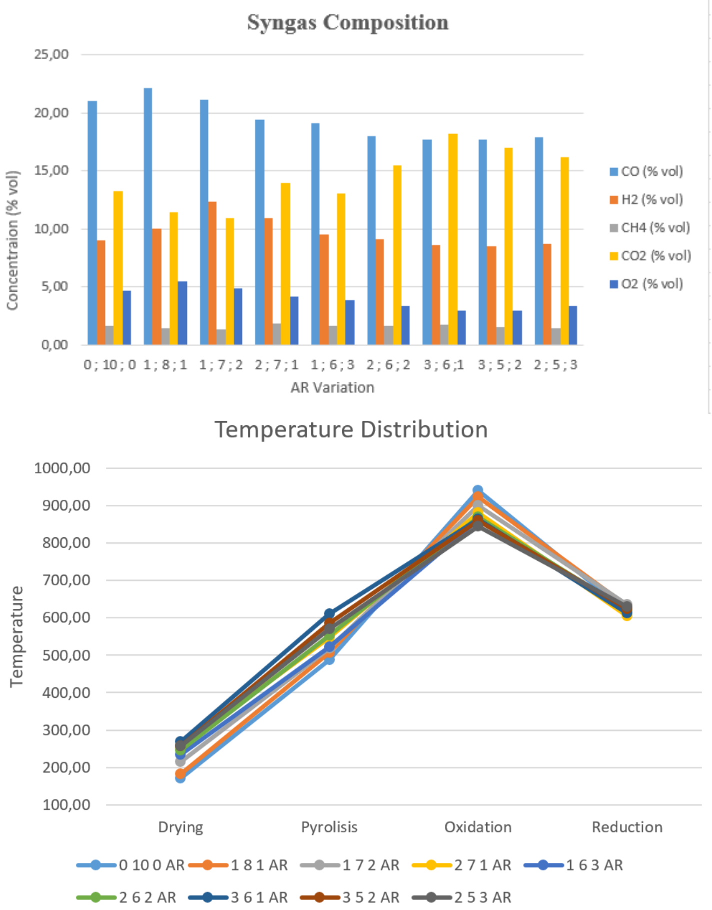


Figure 4.2 Syngas composition vs Temperature Distribution chart.

In table and figure 4.2, syngas composition is shown for every AR variation. At 0 ; 10 ; 0 AR, syngas has a composition of 21,01% CO, 8,98% H_2, 1,65% CH_4, 13,30% CO_2, 50,35% N_2, and 4,71% O_2. Several following variations have increasing composition of flammable syngas, with the peak composition achieved at 1 ; 7 ; 2 AR, with 21,12% CO, 10,06% H_2, 1,33% CH_4, 10,90% CO_2, 49,35% N_2, and 4,91% O_2. Variation 1 ; 7 ; 2 achieved highest amount of H_2 and CH_4 concentration among all variations, while highest CO concentration was achieved in 1 ; 8 ; 2 AR. But after variation 1 ; 7 ; 2, flammable compositions seem to drop dramatically. Increasing content of CO and other flammable gases signifies that a certain amount of introduced air had stimulated partial oxidation reactions in reduction and pyrolysis zone, increasing biomass conversion rate. As stated in previous chapters and sub chapters, in oxidative environment, oxygen tends to react with char, initiating partial oxidation reaction, with CO as its main product, which is advantageous in increasing syngas heating value, since CO is a flammable gas. This increases the quality of the resulting syngas.

Inside the pyrolysis zone, where normally thermal decomposition reactions occur without the aid of air, when air is introduced into the zone, partial oxidation occurs, producing heat, and additional CO gas composition. With additional heat, temperature rises, which increases thermal decomposition reactions, hence increasing volatile gases composition. Higher temperature also improves char conversion reactions rate, increasing gas yield, and reduces char production. Tar cracking reactions also favors higher temperature, reducing tar content, which would in turn improve syngas quality.

Inside the reduction zone, syngas forming reactions occur which form other type of flammable gases, H_2 and CH_4. Inside an oxidative environment, partial oxidation occurs, which produces heat, increasing the zone temperature as seen in the temperature profile data, especially during high input of air. Increasing temperature is favorable for tar cracking reactions, but also favorable for endothermal gasification reactions, such as Boudouard and Water-Gas reactions (Molino, 2015), which is why the composition of CO and H_2 peaked during the peak temperature of reduction zone. Although in some variations this doesn't seem to be the case, for example, AR variations 2;5;3 and 1;8;1 had nearly similar reduction zone temperature, yet they had completely different amount of flammable compositions. This showed that flammable composition may be affected by other factors, such as other zones temperature, or external factors, such as heat loss, uneven oxidant distribution, etc.

Seen from their CO_2 and O_2 content and also higher temperature profile, it can be assumed that later variations stimulated more complete combustion reactions within the gasification zones, with variation which had highest temperature profile, 3 ; 6 ; 1 AR, had the highest CO_2 and lowest O_2 content. This shows that the amount of injected air into pyrolysis and reduction zones could only help up to certain amount, above which excessive air could initiate complete combustion reactions which proves to be unfavorable in gasification process, since it produces CO_2 which has no heating value.

N_2 content tends to be consistent at around 50% above at every AR variation. This is understandable, since N_2 consists a large portion of free air, which is around 75% v, and it's also considered an inert gas and doesn't react with other chemical components easily. Which is why its volumetric content tends to be constant.

Compared to previous research conducted in ITS about three stage air intake, the resulting syngas on this research has more CH_4 content. This is presumably caused by the material used in this research, Oil Palm Fronds (OPF). As stated in a journal by Gafur, 2018, using the same material, the CH_4 composition ranged between 0,97 to 1,91% vol, while in a journal by Ximenes, 2018, it only ranged between 0,95-1,16% vol, using Municipal Solid Waste (MSW) biomass.

4.3. Lower Heating Value (LHV)

Lower Heating Value (LHV) of syngas is influenced by its composition, since each flammable gas component has their own LHV. Their respective LHV can be observed in table 4.3 below.

Table 4.3. Flammable gas LHV.

Flammable gas LHV		
CO (kJ/m^3)	H_2 (kJ/m^3)	CH_4 (kJ/m^3)
12633	10783	35883

From volumetric percentage analysis done on the resulting syngas, its LHV can be calculated using following equations:

$$\boldsymbol{LHV_{Syngas}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (\boldsymbol{Y_i} \, . \boldsymbol{LHV_i})$$

With:

Y_i
$= volumetric\ percentage\ of\ syngas\ components\ (CO, CH_4, H_2)$

LHV_i
$= LHV\ of\ respective\ flammable\ syngas\ components\ (CO, CH_4, H_2)$

Here's an example for LHV calculation using 0 ; 10 ; 0 AR variation :

- Yi of CO = 21,01% = 0,2101
- Yi of H_2 = 8,98% = 0,0098
- Yi of CH_4 = 1,65% = 0,0397

Which makes:

$$LHV\ Syngas = \sum_{i=1}^{n} (0{,}2101\ .\ 12633) + (0{,}0898\ .\ 10783) + (0{,}0165\ .\ 35883)$$

$$LHV\ Syngas = 4214{,}5762\ \frac{kJ}{m^3}$$

Pay attention that the unit of LHV is still in kj/m^3, while we need to convert it to kj/kg for it to be valid. For that, we need to divide the current LHV with the density of syngas.

Syngas is a combination of many gases components, which have different properties including density. Syngas density could be calculated using following formula:

$$\rho_{syngas} = \sum_{i=1}^{n} Y_i \cdot \rho_{i\ syngas}$$

With:

ρ_{syngas} = syngas density (kg/m^3)

Y_i = syngas volumetric percentage

$\rho_{i\ syngas}$ = individual density of syngas components (CO, H_2, CH_4, dll) (kg/m^3)

Here is an example of LHV and syngas density calculation done using 0 ; 1 ; 0 AR variation. The density of necessary gases were taken from A4 Table about thermophysical properties of gases at atmospheric pressure.

21,01 % CO with ρ = 1,0599 kg/m^3
8,98 % H_2 with ρ = 0,07409 kg/m^3
1,65 % CH_4 with ρ = 0,5227 kg/m^3
13,30 % CO_2 with ρ = 1,6676 kg/m^3
50,35 % N_2 with ρ = 1,0339 kg/m^3
4.71 % O_2 with ρ = 1,1890 kg/m^3

$$\begin{aligned}\rho_{syngas} = \sum_{i=1}^{n} & (0{,}2101\ .\ 1{,}0599) + (0{,}0898.\ 0{,}07409) \\ & + (0{,}0165\ .\ 0{,}5227) + (0{,}1330\ .\ 1{,}6676) \\ & + (0{,}5035\ .\ 1{,}0339) + (0{,}0471.\ 1{,}1890)\end{aligned}$$

$$\rho_{gas} = 1{,}0363\ \frac{kg}{m^3}$$

The resulting LHV for all variation is shown in table 4.4 and figure 4.3.

Table 4.4 Syngas LHV results.

AR	Gas LHV			Syngas density	LHV Syngas (kj/kg)
	CO (kj/m3)	H2 (kj/m3)	CH4 (kj/m3)		
0 ; 10 ; 0	12633	10783	35883	1,036324172	4066,851198
1 ; 8 ; 1	12633	10783	35883	1,016950774	4321,192148
1 ; 7 ; 2	12633	10783	35883	0,990360491	4524,965647
2 ; 7 ; 1	12633	10783	35883	1,018729102	4221,666282
1 ; 6 ; 3	12633	10783	35883	1,027037515	3947,426789
2 ; 6 ; 2	12633	10783	35883	1,045366246	3707,246637
3 ; 6 ;1	12633	10783	35883	1,066002615	3570,36929
3 ; 5 ; 2	12633	10783	35883	1,060319344	3524,204402
2 ; 5 ; 3	12633	10783	35883	1,055606008	3513,239383

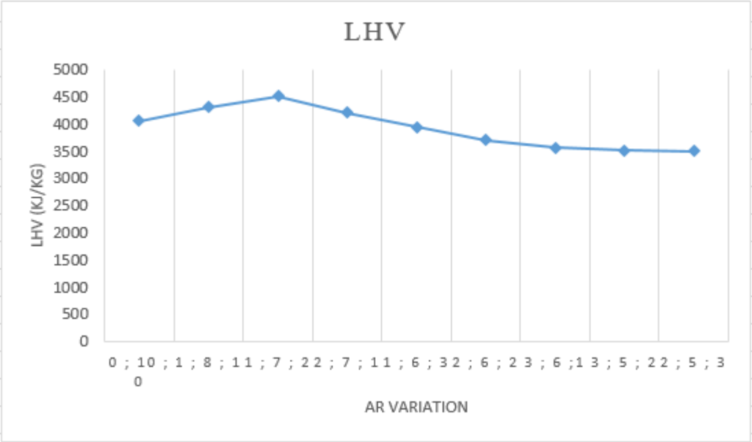


Figure 4.3 Syngas LHV chart

As seen in table 4.4 and figure 4.3, LHV starts to increase from 0;1;0 AR until peak LHV is achieved in 1:7:2 AR variation, which is 4524,97 kj/kg, then it continues to descend in latter variations with the lowest LHV achieved in 2;5;3 AR, which is 3513,24 kj/kg. This figure matches the changes in operation temperature chart, which means that temperature significantly affects the reactions of gasification which directly affects the resulting syngas composition and final heating value.

LHV is heavily affected by syngas composition. Compared to previous research about three stage air intake conducted in ITS by Ximenes, 2018, which has the highest LHV of 4034 kj/kg, the LHV of this research is much higher at 4524,97 kj/kg albeit having slightly lower H_2 content. But on the other hand this research has higher CH_4 content in the resulting syngas, which contributes much to the increased LHV.

4.4. Cold-Gas Efficiency

Cold gas efficiency is a measure of efficiency using energy input over potential energy output. The efficiency is expressed as:

$$Cold\ gas\ efficiency = \frac{\dot{m}_{syngas}.\,LHV_{syngas}}{\dot{m}_{biomass}.\,LHV_{biomass}}$$

Here is an example of Cold-gas efficiency calculation using 0;10;0 AR. Using biomass mass flow of 0,00139 kg/s, syngas mass flow of 0,00266 kg/s, syngas LHV of 4066,85 kj/kg, and biomass LHV of 15731,12 kj/kg, Cold gas efficiency is calculated as:

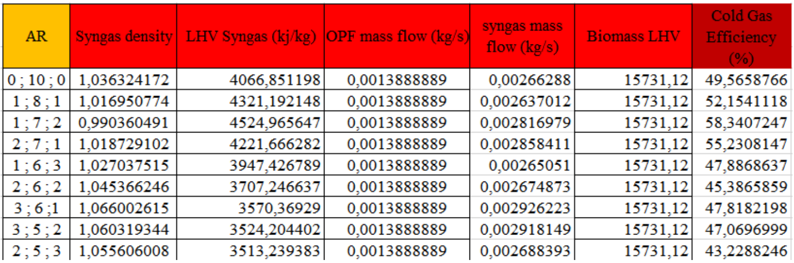
$$Cold\ gas\ efficiency$$

$$= \frac{0{,}00266\ \frac{kg}{s}.\,4066{,}85\ \frac{kj}{kg}.}{0{,}00139\ \frac{kg}{s}.\,15731{,}12\ \frac{kJ}{kg}}\ x\ 100\%$$

$$Cold\ gas\ efficiency = 49{,}566\ \%$$

The remaining cold gas efficiency calculation for every variation can be seen in table 4.5 and figure 4.4.

Table 4.5. Cold gas efficiency for every AR variation



AR	Syngas density	LHV Syngas (kj/kg)	OPF mass flow (kg/s)	syngas mass flow (kg/s)	Biomass LHV	Cold Gas Efficiency (%)
0 ; 10 ; 0	1,036324172	4066,851198	0,0013888889	0,00266288	15731,12	49,5658766
1 ; 8 ; 1	1,016950774	4321,192148	0,0013888889	0,002637012	15731,12	52,1541118
1 ; 7 ; 2	0,990360491	4524,965647	0,0013888889	0,002816979	15731,12	58,3407247
2 ; 7 ; 1	1,018729102	4221,666282	0,0013888889	0,002858411	15731,12	55,2308147
1 ; 6 ; 3	1,027037515	3947,426789	0,0013888889	0,00265051	15731,12	47,8868637
2 ; 6 ; 2	1,045366246	3707,246637	0,0013888889	0,002674873	15731,12	45,3865859
3 ; 6 ;1	1,066002615	3570,36929	0,0013888889	0,002926223	15731,12	47,8182198
3 ; 5 ; 2	1,060319344	3524,204402	0,0013888889	0,002918149	15731,12	47,0696999
2 ; 5 ; 3	1,055606008	3513,239383	0,0013888889	0,002688393	15731,12	43,2288246

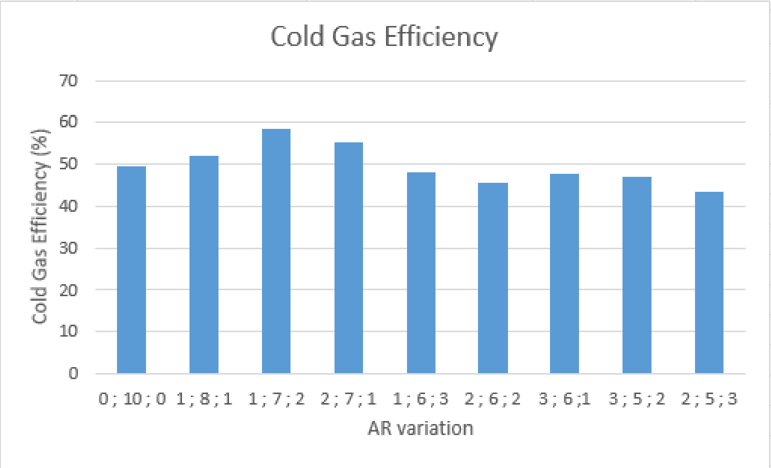


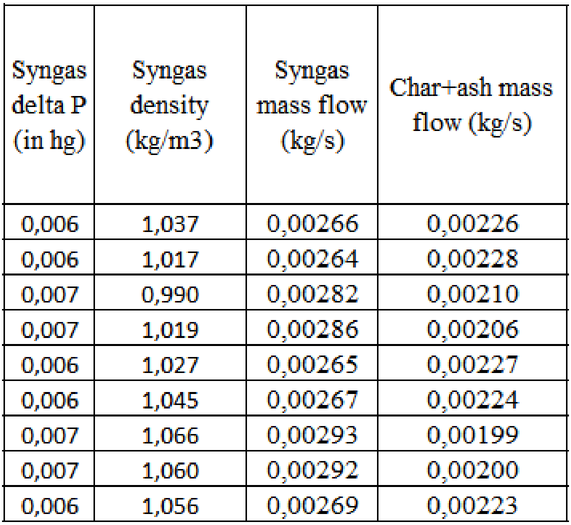
Figure 4.4 Cold Gas efficiency chart.

Table 4.5 and figure 4.4 shows that increasing the amount of air into the pyrolysis and reduction zone can improve cold gas efficiency from initially 49,56% at 0;10;0 AR to 58,34% at 1;7;2 AR, while in latter variations Cold Gas efficiency dropped due to increasing combustion reactions stimulated by increasing oxidant concentration within the pyrolysis and reduction zone, as stated in previous sub chapters, which lowered the flammable contents of syngas.

Cold gas efficiency is influenced by many factors. Mainly, syngas composition, LHV, syngas mass flow, biomass mass flow, and biomass LHV. In this case, syngas mass flow is slightly lower compared to previous researches. Compared to the result acquired by previous research by Ximenes, 2018, which could reach up to 70%, this research cold gas efficiency is slightly lower, which is presumably due to low gas forming reactions activity caused by lower input mass flow.

4.5. Gas Production Rate

Table 4.6. Gas production and solid mass flow rate.



Syngas delta P (in hg)	Syngas density (kg/m3)	Syngas mass flow (kg/s)	Char+ash mass flow (kg/s)
0,006	1,037	0,00266	0,00226
0,006	1,017	0,00264	0,00228
0,007	0,990	0,00282	0,00210
0,007	1,019	0,00286	0,00206
0,006	1,027	0,00265	0,00227
0,006	1,045	0,00267	0,00224
0,007	1,066	0,00293	0,00199
0,007	1,060	0,00292	0,00200
0,006	1,056	0,00269	0,00223

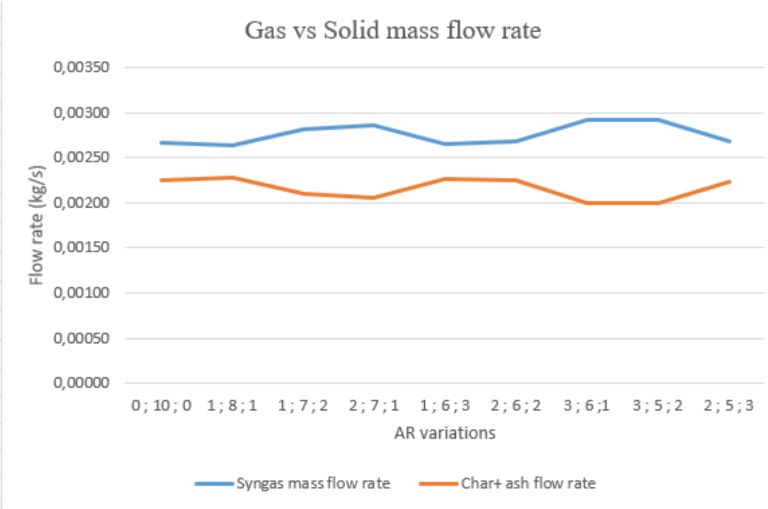


Figure 4.5. Gas vs solid mass flow rate.

Syngas production rate shows the mass flow of the syngas. This parameter can be measured using manometer, although it needs conversion to produce mass flow data. The method of calculation has been explained previously in chapter 3. The result of measurement can be seen in table 4.6 and figure 4.5.

Changes in gas production rate mean there has to be other changes in other mass output parameters, which abide by the law of mass conservation. The mass balance equation in this research's gasification reaction can be stated as:

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\dot{m}_{biomass} + \dot{m}_{intake\ air} = \dot{m}_{char} + \dot{m}_{ash} + \dot{m}_{gas}$$

Which means, a change in gas production rate means changes in char and ash mass flow, which shows that there is a change in char conversion rate and/or ash formation rate. It can be seen in the figure 4.5 that when gas production rate goes up, the solid mass flow rate decreases and vice versa, conforming to mass balance principle. A journal by Zhao, 2014, about oxidative pyrolysis also produced result that increasing oxygen concentration in the pyrolyzer increased gas yield, yet reduced solid yield in the product distribution. Gas production rate in this research however, tends to have relatively constant results with minor change/increase which peaked at 3;6;1 AR variation. Presumably, this shows that gas production rate increased when gas forming reactions activity increased, which, as stated previously, depends on reaction temperature and oxygen concentration, theoretically. Other factors which influence gas forming reaction rate and may cause inadequate change in gas production rate may include, uneven oxidant circulation and distribution, heat loss, etc.

4.6.Tar Content

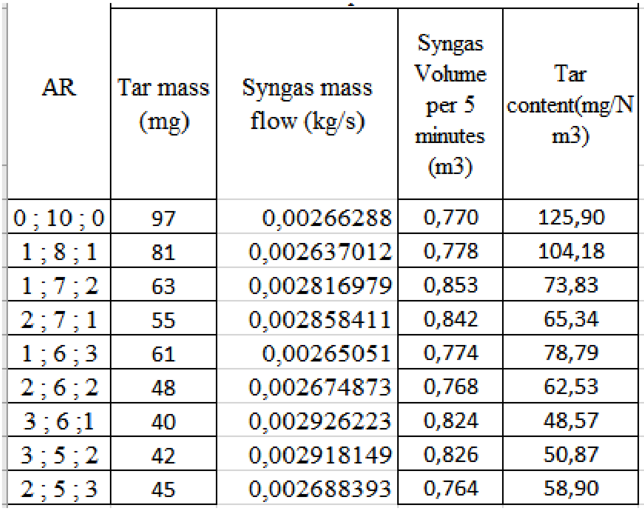
Tar content is the amount of tar contained within a certain volume of syngas, which can be expressed as:

$$Tar\ content = \frac{m_{tar}}{syngas\ volume\ in\ t}$$

Where m_{tar} is stated in mg and syngas volume in Nm^3 (normal cubic meter). Syngas volume is measured for 5 minutes similar to tar condensation data collection. Resulting data is shown in table 4.7 and figure 4.6.

As shown in table 4.7 and figure 4.6, highest tar content was produced in 0;10;0 AR variation with 125,90 mg/Nm^3, while lowest tar content was achieved in 3;6;1 AR, with 48,57 mg/Nm^3.

Table 4.7. Tar content results.



AR	Tar mass (mg)	Syngas mass flow (kg/s)	Syngas Volume per 5 minutes (m3)	Tar content(mg/Nm3)
0 ; 10 ; 0	97	0,00266288	0,770	125,90
1 ; 8 ; 1	81	0,002637012	0,778	104,18
1 ; 7 ; 2	63	0,002816979	0,853	73,83
2 ; 7 ; 1	55	0,002858411	0,842	65,34
1 ; 6 ; 3	61	0,00265051	0,774	78,79
2 ; 6 ; 2	48	0,002674873	0,768	62,53
3 ; 6 ;1	40	0,002926223	0,824	48,57
3 ; 5 ; 2	42	0,002918149	0,826	50,87
2 ; 5 ; 3	45	0,002688393	0,764	58,90

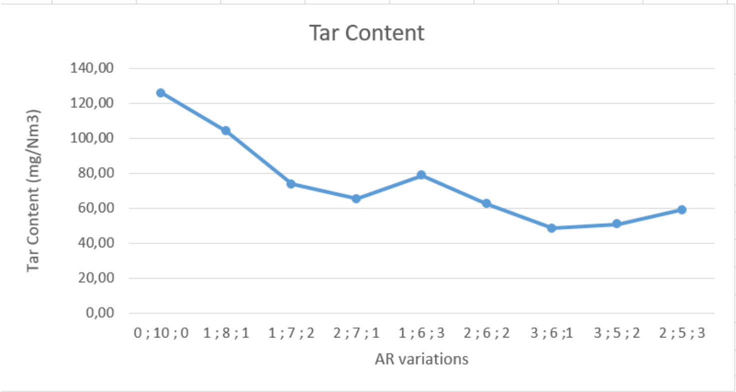


Figure 4.6. Tar content chart.

When compared to the temperature data, this result makes sense, since tar cracking process begins at 500 °C according to

Milne, *et al,* 1998. Also, according to said literature, the higher the temperature in gasifier, the more active tar cracking reaction occurs. Primary tar starts to crack at around 500 °C, secondary tar at 600 °C, while tertiary tar starts cracking at 800 °C. Since 3;6;1 AR variation has the highest temperature profile along the gasifier height, tar can be cracked more thoroughly which makes its tar content the lowest among all variants. While on the other hand, although variation 0;10;0 has the highest oxidation zone temperature, which is 940,50 °C, tar from the other zone presumably hadn't been completely cracked, especially in pyrolysis zone, which has the lowest temperature of all variations of 486,75 °C. This led to high tar content in AR variation 0;10;0.

The tar which was condensed in tar condenser equipment was tar that made it through the dry filter components. Seeing from the tar content of this research, which is 46,41 mg/Nm^3, the syngas can still be deemed allowable for use in internal combustion engine application, according to Milne, *et al,* 1998, which is limited at 100 mg/Nm^3 for internal combustion engine applications.

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the result of the gasification of Oil Palm Fronds (OPF) feedstock using three stage downdraft gasifier, some conclusions can be drawn, which are:

1. Three stage air intake introduced into OPF gasification initiated oxidative pyrolysis and heterogeneous oxidation reaction signified by an increase in temperature in pyrolysis and reduction zone by 124 °C and 20 °C at peak points, respectively, compared to single stage air intake.
2. Three stage air intake improved the performance parameters of gasification measured by following parameters:
   - Flammable composition of resulting syngas improved by following details: CO composition increased from 21,01% v to 22,08% v peak at 1;8;1 AR variation, H_2 composition increased from 8,98% v to 12,39% v peak at 1;7;2 AR variation, and CH_4 composition increased from 1,65% v to 1,87% v peak at 2;7;1 AR variation, compared to the syngas composition at 0;10;0 AR variation.
   - Gas production rate improved from 0,002663 kg/s at 0;10;0 AR variation to 0,00293 kg/s at 3;6;1 AR variation.
   - Low Heating Value (LHV) of syngas improved from 4065,85 kj/kg at 0;10;0 AR variation, to 4524,97 kj/kg peak at 1;7;2 AR variation.

   - Gasification Cold-Gas efficiency improved from 49,57% at 0;10;0 AR variation, to 58,34% at 1;7;2 AR variation.
   - Tar content improved from 125,90 mg/Nm^3 to 48,57 mg/Nm^3 at the lowest at 3;6;1 AR variation.
3. After considering all AR variations, the one deemed to be the most optimal and most suitable for direct application is AR variation 1;7;2, which had the highest number of LHV and Cold-Gas efficiency, 4524,97 kj/kg and 58,34% respectively, while still maintaining its tar content of 73,83 mg/Nm^3 under allowable tar content for ICE application, according to Milne, *et al,* 1998, at around 100 mg/Nm^3.

5.2 Recommendation

Researches about gasification technology still need to be intensified and deepened further. From previously conducted researches, some recommendations can be made, which are:

1. Automation of gasification process must be researched and improved upon, especially in the wake of industrial revolution 4.0.
2. AR variation range must be narrowed down further to find the precise optimum variation for gasification.
3. Better thermal insulation for the gasifier is necessary to prevent heat loss which may hinder gasification operation and analysis.

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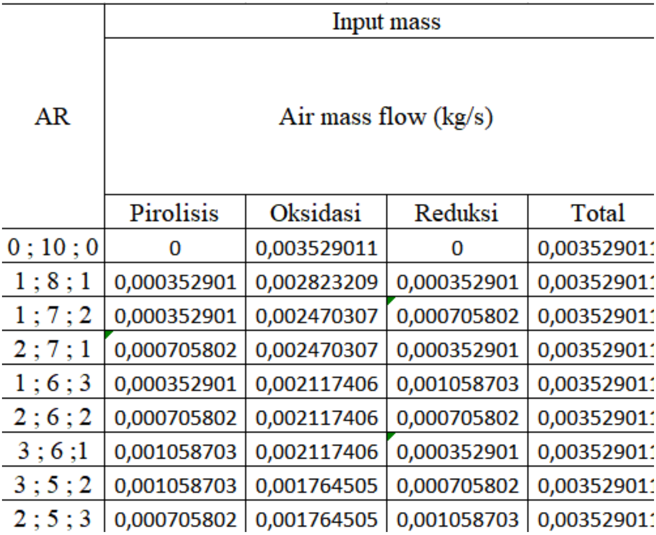
ATTACHMENTS

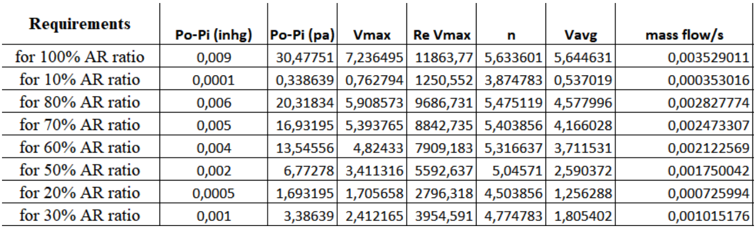
1. Air mass flow calculation table

Required air flow in each AR variations



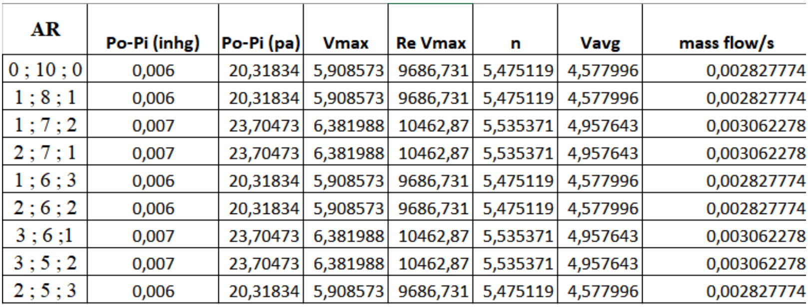
AR	Input mass			
	Air mass flow (kg/s)			
	Pirolisis	Oksidasi	Reduksi	Total
0 ; 10 ; 0	0	0,003529011	0	0,00352901
1 ; 8 ; 1	0,000352901	0,002823209	0,000352901	0,00352901
1 ; 7 ; 2	0,000352901	0,002470307	0,000705802	0,00352901
2 ; 7 ; 1	0,000705802	0,002470307	0,000352901	0,00352901
1 ; 6 ; 3	0,000352901	0,002117406	0,001058703	0,00352901
2 ; 6 ; 2	0,000705802	0,002117406	0,000705802	0,00352901
3 ; 6 ;1	0,001058703	0,002117406	0,000352901	0,00352901
3 ; 5 ; 2	0,001058703	0,001764505	0,000705802	0,00352901
2 ; 5 ; 3	0,000705802	0,001764505	0,001058703	0,00352901

Required Δp reading in manometer



Requirements	Po-Pi (inhg)	Po-Pi (pa)	Vmax	Re Vmax	n	Vavg	mass flow/s
for 100% AR ratio	0,009	30,47751	7,236495	11863,77	5,633601	5,644631	0,003529011
for 10% AR ratio	0,0001	0,338639	0,762794	1250,552	3,874783	0,537019	0,000353016
for 80% AR ratio	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774
for 70% AR ratio	0,005	16,93195	5,393765	8842,735	5,403856	4,166028	0,002473307
for 60% AR ratio	0,004	13,54556	4,82433	7909,183	5,316637	3,711531	0,002122569
for 50% AR ratio	0,002	6,77278	3,411316	5592,637	5,04571	2,590372	0,001750042
for 20% AR ratio	0,0005	1,693195	1,705658	2796,318	4,503856	1,256288	0,000725994
for 30% AR ratio	0,001	3,38639	2,412165	3954,591	4,774783	1,805402	0,001015176

2. Syngas mass flow calculation table



AR	Po-Pi (inhg)	Po-Pi (pa)	Vmax	Re Vmax	n	Vavg	mass flow/s
0 ; 10 ; 0	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774
1 ; 8 ; 1	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774
1 ; 7 ; 2	0,007	23,70473	6,381988	10462,87	5,535371	4,957643	0,003062278
2 ; 7 ; 1	0,007	23,70473	6,381988	10462,87	5,535371	4,957643	0,003062278
1 ; 6 ; 3	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774
2 ; 6 ; 2	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774
3 ; 6 ;1	0,007	23,70473	6,381988	10462,87	5,535371	4,957643	0,003062278
3 ; 5 ; 2	0,007	23,70473	6,381988	10462,87	5,535371	4,957643	0,003062278
2 ; 5 ; 3	0,006	20,31834	5,908573	9686,731	5,475119	4,577996	0,002827774

BIODATA PENULIS

Penulis dilahirkan di Lamongan, Jawa Timur pada tanggal 23 Januari 1997 dan merupakan anak pertama dari tiga bersaudara.

Penulis menempuh Pendidikan dasar di SDN Babat 1, Babat, Lamongan, kemudian melanjutkan studi di SMPN 1 Babat, yang seterusnya dilanjutkan pada pendidikan lanjut di SMAN 1 Lamongan. Pada tahun 2015, penulis diterima di program S-1 Teknik Mesin Fakultas Teknologi Industri Institut Teknologi Sepuluh Nopember untuk mengambil pendidikan perkuliahan.

Selama perkuliahan di ITS, penulis aktif mengikuti kegiatan organisasi Lembaga Bengkel Mahasiswa Mesin ITS. Selama aktif di LBMM ITS, penulis menjabat sebagai staf dan kemudian membantu sebagai pengurus non-inti di masa jabatan berikutnya.