CO-GASIFICATION OF COAL AND BIOMASS (EMPTY FRUIT BUNCH, OIL PALM FROND, AND KEMPAS) IN AN ENTRAINED FLOW GASIFIER

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

Faculty of Chemical & Natural Resources Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2018

ACKNOWLEDGEMENTS

First and foremost, I would like to express my thanks to Almighty ALLAH on the successful completion of this research work and thesis.

I hereby express my sincere and profound gratitude to my supervisor, Dr Ruwaida Binti Abdul Rasid. The supervision, guidance, and support that she gave truly helped the progression and smoothness of my postgraduate research project. The cooperation is much indeed appreciated.

I am grateful to the Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang (UMP) for the support and facilities provided to carry out the experimental work. I am also grateful to the staff of the Environmental Engineering Laboratory for their support, assistance, and friendly treatment that not only facilitated the work, but also made it pleasant.

My fellow friends should also be recognized for their support and assistance regarding our research study, especially Thuraiya Binti Mohd Thaim and Nur Farah Hanim Binti Rahmat. I am grateful to all my family members. I also appreciate the financial support for this Master project provided by the Ministry of Higher Education Malaysia and Universiti Malaysia Pahang (UMP) with Vot Numbers RDU140314 and RDU140323, respectively. Lastly, thanks to Universiti Malaysia Pahang (UMP) for sponsoring my conference with Vot Number PGRS170305.

ABSTRAK

Gasifikasi semakin mendapat perhatian sebagai sumber tenaga alternatif yang berpotensi untuk menghasilkan singas, yang terdiri daripada karbon monoksida (CO) dan hidrogen (H_2) yang sesuai bagi kegunaan industri untuk penghasilan tenaga yang sangat efisien. Penggunaan biojisim dalam proses gasifikasi boleh mengurangkan pencemaran alam sekitar seperti kesan gas rumah hijau. Tambahan pula, ko-gasifikasi biojisim dalam *entrained flow gasifier* ialah pendekatan yang mempunyai kelebihan seperti (i) kadar penukaran yang lebih tinggi, (ii) penghasilan singas bebas tar berkualiti tinggi, (iii) boleh dikendalikan pada suhu tinggi, (iv) sesuai untuk pelbagai biojisim, dan (v) masa tindak balas yang lebih pendek berbanding dengan jenis gasifier lain.

Pengaruh suhu, nisbah kesetaraan (*equivalence ratio*, ER), dan nisbah campuran biojisim dan arang batu terhadap komposisi gas, nilai haba tinggi (*high heating value*, HHV) dan kecekapan gas dingin (*cold gas efficiency*, CGE) dikaji. Dalam kajian ini, pengaruh suhu dan ER terhadap jenis biojisim yang berbeza menggunakan *entrained flow gasifier* telah dikaji. Suhu dikawal pada 700 hingga 900 °C dan ER diuji dalam lingkungan 0.2 hingga 0.4 menggunakan bahan mentah biojisim seperti tandan kelapa sawit (EFB), pelepah kelapa sawit (OPF), dan sisa kayu, *Koompassia malaccensis* (Kempas). Selain itu, pengaruh campuran arang batu dan biojisim turut dilakukan. Kesan nisbah biojisim berbeza untuk B0 (100% arang batu) kepada B100 (100% biojisim) pada suhu 700 hingga 900 °C menggunakan EFB. Kesan ko-gasifikasi biojisim dan arang batu untuk pelbagai nisbah campuran biojisim B0 (100% arang batu) kepada B100 (100% biojisim) pada suhu 900 °C menggunakan EFB, OPF, dan Kempas dalam *entrained flow gasifier* juga dijalankan. EFB dan OPF diambil dari LCSB Kilang Sawit Lepar Hilir, Kuantan dan sisa kayu diambil dari Kilang Kayu Gambang, Kuantan. Arang batu yang digunakan diambil daripada TNB Bangi.

Eksperimen dijalankan dalam skala makmal pada tekanan atmosfera dalam sistem *entrained flow gasifier*. Sampel dimasukkan ke dalam reaktor secara manual pada sistem separa kelompok pada kadar aliran udara yang diinginkan bergantung kepada ER. Bekalan udara ke gasifier dicampur dan dikawal dengan menggunakan dua buah meter aliran dan dua buah injap. Suapan skru digunakan untuk memasukkan sampel dan motor untuk mengawal kelajuan suapan skru. Relau berbentuk silinder dengan diameter 4.5 cm dan panjang 50 cm dibuat daripada keluli tahan karat yang boleh menahan suhu sehingga 1100 °C. Gasifier juga dilengkapi dengan siklon untuk mengeluarkan gas kotor yang mengandungi abu, arang, tar, dan zarah habuk melalui pemisah siklon. Siklon itu digunakan untuk mengasingkan abu dan arang dari gas dan dibawa ke pengumpul abu utama dan kedua yang terletak di bahagian bawah siklon. Gas yang melalui siklon akan memisahkan gas dan abu yang dihasilkan dari gasifikasi biojisim. Gas panas kemudian melalui kondenser untuk menurunkan suhu gas sebelum gas dikumpulkan dalam beg sampel. Kromatografi gas–pengesan konduktiviti haba (*gas chromatography–thermal conductivity detector*, GC–TCD) digunakan dalam kajian ini untuk mengenalpasti komposisi gas (H_2, CO, dan CO_2) daripada tindak balas. Komposisi gas dapat ditentukan berdasarkan faktor-faktor yang diberikan oleh GC–TCD seperti masa penahanan, luas, jumlah/luas, dan jumlah.

Melalui kajian ini, didapati bahawa suhu dan ER sangat mempengaruhi pengeluaran singas apabila menggunakan EFB dalam *entrained flow gasifier*. Pengeluaran H_2 dan CO meningkat manakala CO_2 menurun apabila suhu meningkat dari 700 kepada 900 °C.

Sebaliknya, apabila ER terlalu tinggi, lebih daripada 0.3, pengeluaran H_2, CO, dan CO_2 berkurangan sedikit. Selain itu, HHV dan CGE didapati mencapai nilai tertinggi apabila suhu 900 °C dan ER 0.3. Untuk campuran EFB dan batu arang Adaro, pada nisbah biojisim antara B30 dengan B50 dan suhu lebih tinggi daripada 850 °C, pengeluaran singas (H_2 dan CO) adalah maksimum. Bagaimanapun, pengeluaran CO_2 dilihat hampir sama pada variasi suhu dan nisbah biojisim. Di samping itu, nisbah biojisim pada B30 (30% biojisim) mempunyai HHV dan CGE maksimum, yang menunjukkan kesan sinergi. Tambahan pula, peningkatan suhu dan nisbah biojisim mempengaruhi pengeluaran singas daripada OPF dan Kempas. Pengeluaran H_2 daripada Kempas jauh lebih tinggi berbanding dengan penghasilan daripada OPF. Namun, pengeluaran CO dan CO_2 adalah hampir sama bagi kedua-dua biojisim itu. Pada suhu 900 °C, pengeluaran H_2 dan CO adalah yang tertinggi. Selain itu, nilai HHV dan CGE dilihat menurun selepas mencapai nilai maksimum pada nilai ER melebihi 0.3. Di samping itu, nisbah biojisim sangat mempengaruhi hasil singas daripada bahan mentah yang berbeza. Nisbah B30 dapat menghasilkan jumlah singas tertinggi, manakala pengeluaran CO_2 tertinggi ialah pada nisbah B0. Kempas mempunyai pengeluaran H_2 tertinggi manakala EFB mempunyai pengeluaran CO tertinggi. Begitu juga, HHV dan CGE juga dilihat mempunyai nilai tertinggi pada B30, yang merupakan satu lagi petunjuk kesan sinergi pada B30.

ABSTRACT

Gasification is getting more attention as a potential source of alternative energy through the production of syngas, mainly consists of carbon monoxide (CO) and hydrogen (H_2) which is suitable for industrial application for highly efficient energy production. The utilization of biomass in a gasification process can reduce the environmental pollution such as the greenhouse gas. Furthermore, biomass co-gasification in an entrained flow gasifier is a promising approach due to its advantages which are (i) higher conversion rate, (ii) high quality tar-free syngas, (iii) can be operated at high temperature, (iv) suitable for various feedstock, and (v) shorter residence time compared with that of other types of gasifier.

The influences of temperature, equivalence ratio (ER), and biomass ratio on gas composition, higher heating values (HHV), and cold gas efficiency (CGE) were studied using an entrained flow gasifier. The temperature was controlled between 700 and 900 °C and the ER values were tested in the range of 0.2 to 0.4 for biomass feedstock such as empty fruit bunch (EFB), oil palm frond (OPF) and forest residue *Koompassia malaccensis* (Kempas). Moreover, the co-gasification of coal and biomass was also studied for the effect of biomass ratio and temperature varied from B0 (100% coal) to B100 (100% biomass) at the temperature of 700 to 900 °C. The co-gasification of various biomass and coal was also studied at the fixed temperature of 900 °C using EFB, OPF, and Kempas in an entrained flow gasifier. The EFB and OPF were collected from Kilang Sawit LCSB Lepar Hilir, Kuantan, and Kempas was collected from Kilang Kayu Gambang, Kuantan. The coal was obtained from TNB Research Bangi.

The experiments were performed in a laboratory scale entrained flow gasification system at atmospheric pressure. The samples were put in the reactor on a semi-batch system under the desired airflow rate depending on the ER through manual loading. The air supply to the gasifier was mixed, controlled, and monitored by using two flow meters and two valves. A screw feeder was used to feed the sample and a motor was used to control the speed of the screw feeder. The furnace was cylindrical with an inside diameter of 4.5 cm and a length of 50 cm made by stainless steel which can withstand temperature up to 1100 °C. The gasifier was also equipped with a cyclone where the dirty outlet gas containing ash, char, tar, and dust particles entered the cyclone separator. The cyclone was used to remove ash and chars from the gas and derived them into the primary and secondary ash collectors which were located at the bottom of cyclone. The gas was passed through the cyclone to separate the gas and ash produced from the gasification of biomass. The hot gas was then passed through the condenser to reduce the temperature of gas before the gas was collected in gas sampling bags. Gas chromatography equipped with a thermal conductivity detector (GC–TCD) was used to quantify the gas composition (H_2, CO, and CO_2) produced from the reaction. The gas compositions may be determined on the basis of the properties given by GC–TCD such as retention time, area, amount/area, and amount.

It was found that temperature and ER highly affected the production of syngas using EFB in an entrained flow gasifier. The production of H_2 and CO increased while CO_2 decreased as the temperature was increased from 700 to 900 °C. Conversely, when the ER was too high, more than 0.3, the production of H_2, CO, and CO_2 slightly decreased. Furthermore, the HHV and CGE achieved their highest values at 900 °C and ER of 0.3. For the co-gasification of EFB and Adaro coal, when the biomass ratio was increased between B30 and B50 and the temperature was higher than 850 °C, the production of syngas (H_2 and CO) was observed to be at its maximum. However, the CO_2 production was seen to be almost unchanged throughout the variation of temperature and biomass ratio. Additionally, the biomass ratio of B30 (30% biomass) was observed to have the maximum HHV and CGE, which implies the presence of the synergistic effects at B30. Furthermore, it was observed that the increase of temperature and biomass ratio influenced the production of syngas from OPF and Kempas. The production of H_2 from Kempas was significantly higher compared with that of OPF. Yet, the production of CO and CO_2 was nearly the same for both biomasses. At 900 °C, the production of H_2 and CO were the highest. Moreover, the HHV and CGE values decreased after reaching the maximum value of ER above 0.3. In addition, it was proven that the biomass ratio highly affected the product syngas from different feedstocks. At B30, it was able to produce the highest amount of syngas, whereas the CO_2 production was the highest at B0. Kempas had highest H_2 production while EFB had the highest CO production. Similarly, the HHV and CGE values for all sample mixtures were also the highest value at B30, which is another indication of the presence of the synergistic effects at B30.

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LIST OF ABBREVIATIONS

C_2+	Hydrocarbons
C_2H_4	Ethylene
CCE	Carbon conversion efficiency
CGE	Cold gas efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
CO/CO_2	Carbon monoxide to carbon dioxide ratio
CV	Calorific value
EFB	Empty fruit bunches
ER	Equivalence ratio
FC	Fixed carbon
GC	Gas chromatography
H_2	Hydrogen
H_2/CO	Hydrogen to carbon monoxide ratio
H_2/CO_2	Hydrogen to carbon dioxide ratio
H_2O	Water
H_2S	Hydrogen sulfide
HHV	Higher heating value
LHV	Lower heating value
MC	Moisture content
N_2	Nitrogen
NH_3	Ammonia
NO_x	Oxides of nitrogen
OPF	Oil palm fronds
O_2	Oxygen
PA	Proximate analysis
PKC	Palm kernel cake
POME	Palm oil mill effluent
S/B	Steam to biomass ratio
SO_x	Oxides of sulfur
SO_2	Sulfur dioxide
UA	Ultimate analysis

VM	Volatile matter
WGS	Water-gas shift

CHAPTER 1

INTRODUCTION

1.1 Background

Biomass an abundant and environmentally friendly resource for renewable energy and it may be an ideal alternative to fossil fuels for hydrogen (H_2) and syngas (H_2 and CO) production (Cohce et al., 2010). The total oil palm plantation area in 2017 is around 5.81 million hectares, which increased about 1.3% from 5.74 million hectares in 2016. Based on MPOB statistics, the total exports of oil palm products rose 2.9% to 23.97 million tonnes in 2017 from 23.29 million tonnes exported in 2016 (MPOB, 2018). Nowadays, Malaysia is the second largest palm oil producer at 39% and exporter for 44% of the world production (Rosenani et al., 2016). Biomass is quickly moving towards the mainstream as an alternative source of energy and has been gathering momentum since the 1970s oil crisis. About 90% of global palm oil production is led by Malaysia, Indonesia, and Thailand, which generate 27 million tonnes of waste per annum in the form of empty fruit bunch (EFB), fibers, and shells, as well as liquid effluent. In general, oil palm tree produces 90% of biomass feedstock which mainly consist of EFB, mesocarp fiber, palm kernel shells (PKS), and palm kernel cake (PKC) (Zafar, 2018). Thus, the palm oil industry generates an abundant amount of by-products (Aziz & Mun, 2012).

The biomass availability in Malaysia can be categorized into three different sectors, which are from agriculture, forestry, and waste sources. For the agriculture sector, there are two types of biomass categories, which are primary crop and secondary agriculture residue, for example, kenaf, sago waste, palm kernel, and palm oil mill effluent (POME). Examples of residues from the cultivation and harvesting of forest products are wood chips and saw dust (MIGHT, 2013). Other waste sources come from maintenance activities, organic household wastes such as food waste, food processing residues from markets, wood cuttings and fractions from construction, and municipal sewage sludge (MIGHT, 2013). An overview of biomass categories available from the three sectors is summarized in Table 1.1.

Table 1.1 Overview of biomass in Malaysia

Sector	**Biomass Category**	**Biomass Types**	**Description**
Agriculture	Primary crop	Woody biomass	Kenaf, bamboo
		Sugar, starch, oil	Jatropha, sago waste, oil palm trunk juice
	Secondary agriculture residue	Solid agriculture residue	EFB, mesocarp fiber, PKS, paddy straw, husk
		Wet biomass	POME, sago sludge, pig/cattle/chicken manure
Forestry	Primary forest residues	Woody biomass	Residues from cultivation and harvesting/logging activities (off-cuts, branches)
	Secondary forest residues		Wood chips, saw dust
Waste	Primary residues	Landscape waste	Biomass residues from maintenance activities (green and woody cuttings)
	Tertiary residues	Household organic waste	Organic household waste, e.g., food waste, waste papers
		Industrial organic waste	Food processing residues from trade, markets
		Industrial biomass	Woody fractions from construction, demolition, bulk transport activities
		Wet biomass	Sewage sludge

Source: MIGHT (2013)

Malaysia and Indonesia are two major producers of palm-based biomass (Hossain et al., 2017). The potential of utilizing palm-based biomass can be highlighted because only 10% actually produces the oil while the other 90% is in the form of biomass waste. Approximately, 21.625 tonnes of wastes are generated from one hectare of oil palm plantation annually (Hosseini et al., 2015). The distribution of the wastes are as follows:

78% OPF, 9% EFB, 6% mesocarp fiber, 5% palm oil trunks, and PKS, as illustrated in Figure 1.1.

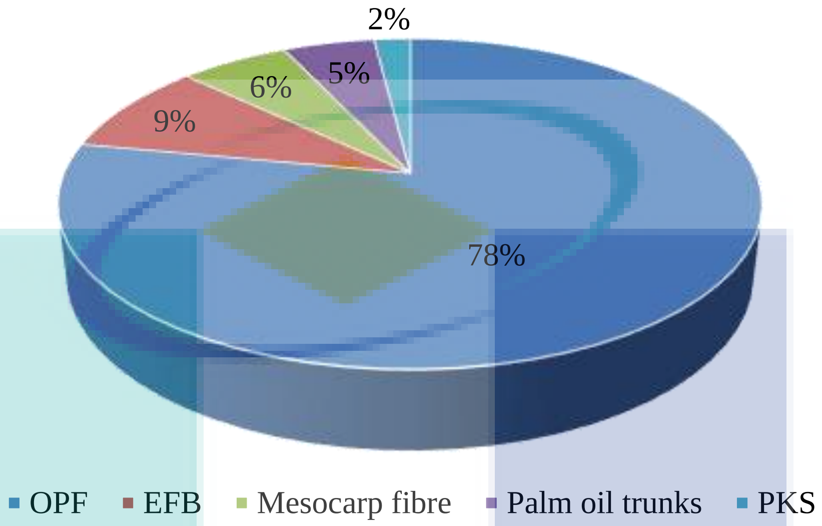


Figure 1.1 Palm solid residue distribution from palm oil in Malaysia

Source: Hosseini et al. (2015)

Koompassia malaccensis or locally known as Kempas is one of the major timber species widely scattered throughout Malaysia and Indonesia (Wiemann, 2010). In 2016, the total production of forest products in Malaysia was estimated to be 7.36 million cubic meters. From this number, 4.45 million cubic meters was from log industries, 2.48 million cubic meters was from sawn timber, and plywood and moldings produced 0.36 and 0.07 million cubic meters, respectively (FDPM, 2017). Figure 1.2 shows the export of major timber by Malaysia in 2017. This indicates the high amount of the forestry waste in Malaysia.

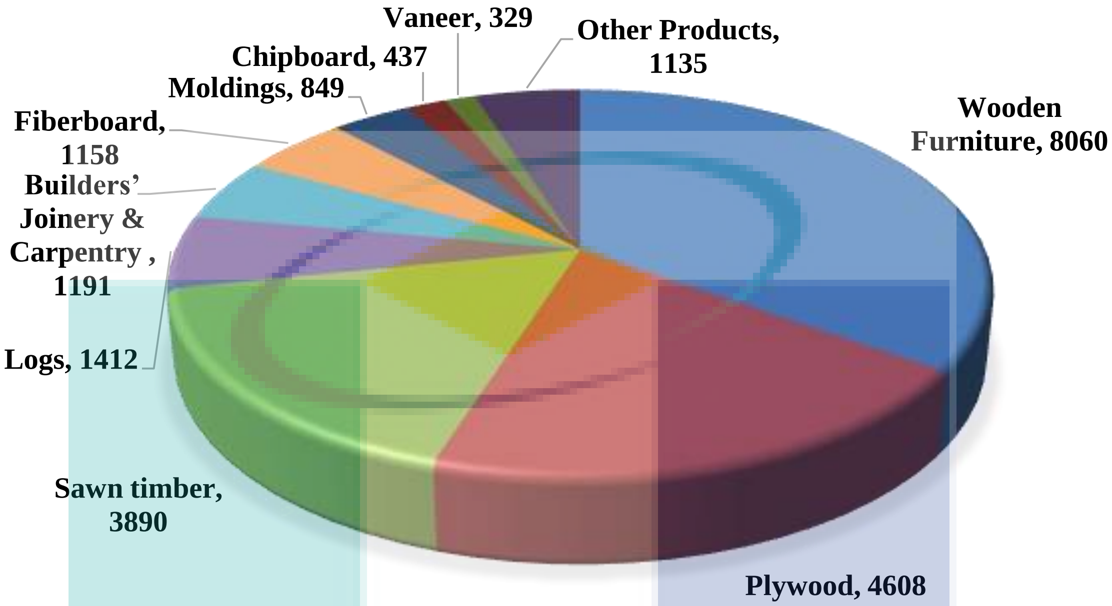


Figure 1.2 Export of major timber in Malaysia

Source: MTIB (2018)

The depletion of the world's fossil fuel has caused the focus on coal has less compared to biomass as it is a form of renewable energy in the past few decades. Nevertheless, coal is used as the feedstock in electric power plants throughout the world. Coal mainly consists of carbon, hydrogen, and oxygen, while biomass is a complex compound that contains cellulose, lignin, hemicellulose, extractives, and minerals (Velez et al., 2009). There is a major difference in the composition of coal and biomass in terms of fixed carbon, volatile matter, and ash (Mallick et al., 2017). In addition, coal has a higher energy content and carbon content compared to biomass (Li et al., 2010).

One of the technology that has been established to be able to convert these solid fuels into useful products is the gasification technology. Gasification is a thermochemical process currently available for alternative fuel production, where it converts solid carbonaceous materials to a synthesis gas, a gas mixture rich in hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), by partial oxidation at elevated temperature (Sheth & Babu, 2009). However, there are still some challenges for gasification technology, such as the ash behavior and formation of soot and tar. This is more evident in the utilization of biomass compared to the most established coal gas technology; the entrained flow gasification process operates at a higher temperature than the fixed and fluidized bed with smaller particles. Entrained flow gasifiers usually operate at temperatures higher than 1200 °C, have higher carbon conversion, and produce high quality syngas with low CH_4, CO_2, and tar (Higman & Burgt, 2008; Henrich & Weirich, 2004).

1.2 Motivation

Today, numerous nations depend heavily on fossil fuels and nuclear power to generate their electricity. This will result in a system that lacks diversity and security, threatens the health of the mankind, risks the stability of Earth's climate, and deprives the future generations of clean air, clean water, and energy independence. Luckily, the renewable energy resources such as wind, solar, biomass, and geothermal are capable to fulfill the world’s energy needs and help reduce many of the problems.

Rapid development of technology and industrialization has caused the reduction of fossil energy resources and is severely affecting the environment. Fossil fuel is the most common energy source used in the world. Over 80% of the energy demand and consumption reported counts for fossil fuels (Escobar et al., 2009). Fossil fuels release a significant amount of pollutants such as CO_2, nitrogen oxides (NO_x), and sulfur oxides (SO_x) into the atmosphere (Demirbas, 2007). Burning of fossil fuels emits large amount of CO_2 which causes greenhouse gas effects and global warming (Escobar et al., 2009). With the present rate of energy consumption, it is estimated that the world’s oil reservoir will run out by 2050 (Demirbas, 2007; Saxena et al., 2009).

The gasification products, syngas, are mainly CO, H_2, and other gases such as CO_2, CH_4, H_2O, and higher hydrocarbons, as well as particles, ash, and tars. The process takes place in an environment with limited oxygen, which limits the formation of dioxin and high quantities of SO_x and NO_x (Jangsawang et al., 2006). Biomass wastes are usually burnt in open air or released which generate pollutants including greenhouse gases, dust, and a large amount of methane, which is a more vigorous greenhouse gas than CO_2. Moreover, burning of fossil fuels emits a large amount of CO_2 which causes the greenhouse gas effects that contribute to global warming (Escobar et al., 2009). Therefore, in developed countries, there is a growing trend towards the use of biomass-based energies to overcome these issues (Escobar et al., 2009). One of the promising technologies which can be applied for the biomass wastes is gasification. Although biomass as a renewable energy still has a far way to go to substitute fossil fuels and become the primary source of energy consumption, there are several important reasons as to why it should be done for the development of renewable energy in the future of our society (Alauddin et al., 2010).

1.3 Problem Statement

Biomass can be used as an alternative energy source to reduce the dependence on decreasing fossil fuel sources such as coal, oil, and natural gas. With more than 423 palm oil mills in Malaysia, palm oil industry produced around 80 million dry tons of biomass in 2010 (Aziz & Mun, 2012). From the palm oil processing yield, only 10% are the final products (palm oil and palm kernel oil) while the remaining 90% are harvestable biomass waste in the form of EFB, PKS, POME, and PKC (Aziz & Mun, 2012). This overload of biomass waste causes an abundance of waste which affects the environment.

The gasification process may be used to overcome this problem as it produces syngas which is commonly composed of CO_2, CO, H_2, and CH_4. Water and nitrogen can also be present depending on the gasification agents such as air, steam, and oxygen. Besides these gas species, there are other non-desirable products present due to this reaction, such as a mixture of diverse aromatic and polyaromatic compounds, tar, alkali, ammonia, solid fine particles, and heavy metal compounds (Jong, 2008). The release of large amount of CO_2 from the combustion of fossil fuels causes greenhouse effect and global warming (Alauddin et al., 2010).

Various types of gasifier and technologies have been investigated for different fuels. However, gasification of biomass is more challenging compared to fossil fuel because of the complex lignocellulosic structure in the biomass (Samiran et al., 2016). There are a few types of gasifier that can be used for all types of biomass feedstock and one of them is an entrained flow gasifier. An entrained flow gasifier is operated at high temperature to achieve high levels of fuel conversion. Besides that, the high temperature causes low tar formation but requires higher quality gasifier materials. Therefore, utilization of entrained flow gasifier for co-gasification of coal and biomass is highlighted in this research due to its advantages and suitability with the feedstock chosen.

1.4 Objectives

The objectives of this study are as follows:

i. To analyze the co-gasification of coal and biomass in an entrained flow gasifier.

ii. To investigate the effect of gasification temperature and ER for different types of biomass in an entrained flow gasifier.

1.5 Scopes of Studies

i. To investigate the biomass gasification for the effect of operating temperature at the range of 700 to 900 °C and ER at the values of 0.2, 0.25, 0.3, 0.35, 0.4 using EFB, Kempas, and OPF.

ii. To analyze the co-gasification of biomass and coal for various biomass ratios of B0 (100% coal) to B100 (100% biomass) (B0, B10, B30, B50, and B100) for temperatures from 700 to 900 °C using EFB.

iii. To determine the co-gasification of biomass and coal for various biomass ratio of B0 (100% coal) to B100 (100% biomass) (B0, B10, B30, B50, and B100) at 900 °C using EFB, OPF, and Kempas.

1.6 Organization of this thesis

The remainder of the thesis is outlined as follows:

In Chapter 2, a review of the literature is presented to provide an overview of the gasification process and reactions involved. The various types of gasifier used are briefly explained which include entrained flow gasifier, fluidized bed gasifier, and fixed bed gasifier. Moreover, in this chapter, detailed descriptions of previous studies on biomass gasification and co-gasification of coal and biomass are presented, along with their summaries, based on the two most influential parameters: the temperature and ER. The effect of biomass ratio on co-gasification is also discussed in this chapter.

In Chapter 3, the materials used in the experimental work and the procedures involved to carry out the experiment which include preparation of samples and biomass gasification process are presented. The procedures are summarized in flowcharts. Besides that, analyses methods and procedures for the raw biomass and gasification products are also described in this chapter.

Chapter 4 is the results and discussion of this work. The results of this work are thoroughly discussed, with supports from previous studies. The trends of the results are compared and explained with figures and graphs for a better understanding. In addition, other specific analyses from the results are also made, including the ultimate analysis, higher heating value product gas, and cold gas efficiency to demonstrate the overall outcome of the experimental works.

Chapter 5 concludes the findings and provides recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Biomass

Biomass is defined as biological materials derived from living organism such as animals and plants (Ahmad et al., 2016). Among the primary energy sources in the world such as coal, oil, and natural gas, biomass is currently catering for about 14% of the world's total energy consumption and it is ranked as the fourth energy source (Alauddin et al., 2010). Hence, it is an important source of energy, especially to reduce the dependence on fossil-based energy (Bhavanam & Sastry, 2011). The burning of fossil fuels takes carbon that was locked away underground (as crude oil, gas, and coal) and transfers it into the atmosphere as CO_2. The release of large amount CO_2 from combustion of fossil fuels causes greenhouse effect and global warming.

Biomass can be used to generate electricity, heat, and vehicle fuel, and can also be the feedstock for several chemical industries. Biomass is also an important alternative to coal, but it has a few different characteristics from coal in many important aspects, including lower carbon content, higher oxygen content, higher volatile content, lower heating value, and lower bulk density (Qin, 2012). The key differences in the properties of biomass in comparison with coal are that biomass is greater in moisture, O, and H content; lower heating value and ash; lower S and N content; lower bulk density, thus making the transportation and storage costs higher; higher volatile matter; and higher reactivity (Demirbas, 2007; Valero & Uson, 2006). Size, shape, and structure are examples of the characteristics of biomass that affect the rate of gasification. Biomass with a small size is better for controlling reaction temperatures and as a result maximizes the rate of the gasification reaction. However, the limitation in size is very important for controlling both the temperature and the reaction rate.

In terms of the environmental effects, biomass fuels possess a negligible sulfur concentration, produce less ash, and generate far less air emissions in comparison with fossil fuels. Therefore, the combustion of biomass does not contribute to SO_x emission, which is the cause of acid rain, and the produced ash can be used as a soil additive for selected farms. Besides, the reduction on the dependency on fossil fuels, such as oil, would reduce the economic pressures of importing petroleum products (Demirbas, 2001).

2.2 Biomass Types

The most potential source of renewable energy in Malaysia comes from biomass. Being one of the main palm oil producers in the world, enormous output from the palm oil industries as well as forestry residues are available to be utilized as shown in Figure 2.1. As much as 16% of the energy supply originates from biomass fuels, in which 51% is from palm oil wastes, while 22% comes from agricultural resources (Husain et al., 2003). Thus, agriculture sources may be considered to be the most potential source for alternative energy due to their abundance in Malaysia.

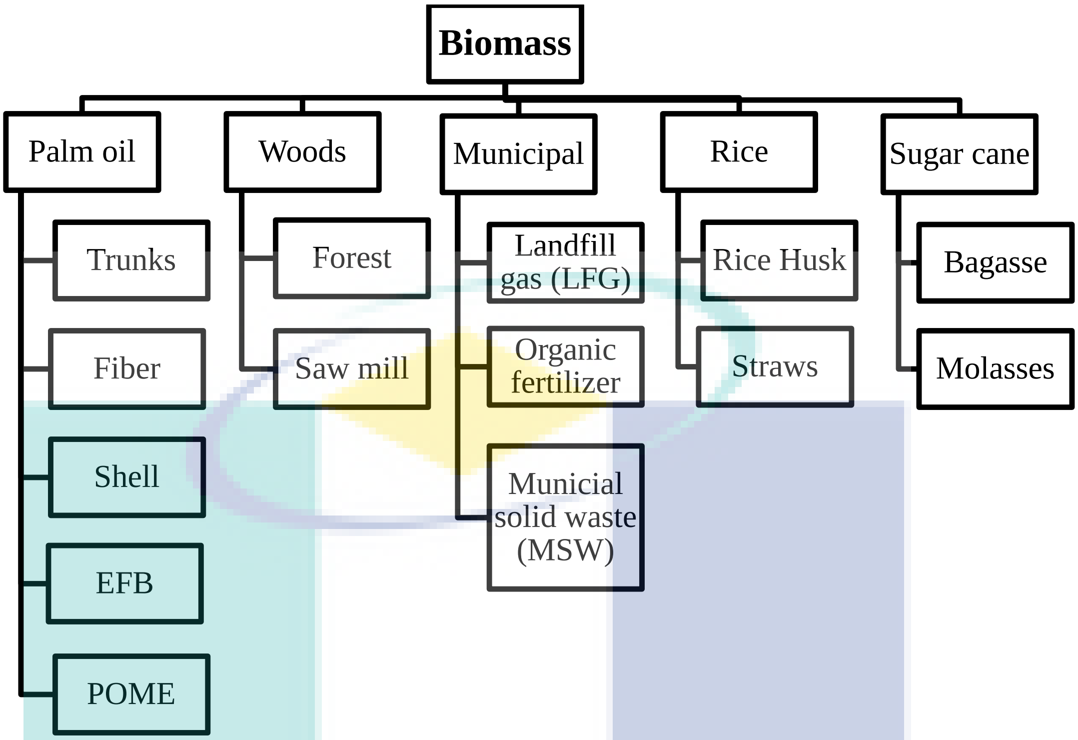


Figure 2.1 Major biomass energy resources in Malaysia
Source: Petinrin & Shaaban (2015)

2.2.1 Empty Fruit Bunch

EFB, OPF, mesocarp fiber, PKS, and paddy straw are examples of agricultural biomass. One third of the oil palm biomass is EFB while the other two thirds are oil palm trunks and fronds (Husin et al., 2002; Yusoff, 2006). EFB contains neither chemical nor mineral additives, and depending on proper handling operations at the mill, it is free from foreign elements such as gravel, nails, wastes, and wood residues. However, the moisture content in EFB is quite high at approximately 67%, hence, preprocessing is necessary before EFB can be considered as a viable fuel (Salman, 2015). The EFB from the palm oil mill typically contains 30.5% lignocellulose, 2.5% oil, and 67% water; whereas the main constituents of the lignocellulose are cellulose, hemicellulose, and lignin, which are physically hard and strong (Gunawan et al., 2009). On the other hand, PKS and mesocarp fibers also have the potential to be used as solid fuel feedstock for steam generation and to produce electricity due to their high elemental carbon content (Parshetti et al., 2013).

2.2.2 Oil Palm Frond

Compared to other oil palm biomass such as EFB, shells, and trunks, OPF has the highest cellulose and lowest lignin and ash contents (Guangul et al., 2012). OPF mainly consists of 40%–50% cellulose, 20%–30% hemicellulose and 20%–30% lignin (Abnisa et al., 2011). The most unconverted matter in ash and tar is from lignin due to its properties; it is the most difficult component to be thermally decomposed (Burhenne et al., 2013; Garcia-Maraver et al., 2013). Thus, it is advantageous for OPF to be used as gasification fuel due to the high cellulose and low lignin and ash composition in OPF (Burhenne et al., 2013). Table 2.1 presents the moisture content and heat value generated by the palm oil waste.

Table 2.1 Heating value generated from the palm oil waste

Biomass	Moisture content (%)	Heating value (dry) (MJ/kg)
EFB	67.00 ± 1.41	18.88 ± 0.74
Fiber	37.09 ± 2.06	19.06 ± 0.32
PKS	12.00 ± 1.08	20.09 ± 0.43
OPF	70.60 ± 5.58	15.72 ± 0.26
POME	93.00 ± 1.67	16.99 ± 0.58

Sources: Loh (2017)

2.2.3 *Koompassia malaccensis* (Kempas)

Wood and saw dusts are examples of forest residues which may be considered as one of the biomass resources that can be converted to useful energy, both of which come from sawmills. The calorific value for wood is relatively low which is around 19 GJ/dry tonne. In addition, wood has moisture content around 55% by weight when harvested (Watson et al., 2002). *Koompassia malaccensis* or locally known as Kempas is one of the major timber species widely scattered throughout Malaysia and Indonesia (Wiemann, 2010). Kempas is a deciduous tree; it usually grows up to 45 m tall, though can occasionally reach up to 60 m. The straight, cylindrical bole can be free of branches for up to 25 m, 60–149 cm in diameter with steep, plank-like, thick buttresses up to 6 m high. The tree is often harvested from the wild for its wood, which is a useful timber species for heavy construction and is currently gaining importance in trade because of the shortage of heavy hardwood timbers. The plant is classified as “Least Concern” in the IUCN Red List of Threatened Species (2013) (National Parks, 2018). Table 2.2

summarizes the energy content for different types of wood product which shows that freshly harvested wood is the lowest with values of 4.7–7.4 GJ/m^3.

Table 2.2 Energy content ranges for different wood fuel products

Product	**Energy Content (GJ/m^3)**
Freshly harvested wood	4.7–7.4
Oven dry wood	7.6–10.5
Wood pellet	7.8–10.5
Torrefied wood pellet	14.9–18.4
Bio-oil	19.2–22.8

Source: Horgan (2009)

2.3 Coal

Coal mainly consists of carbon, hydrogen, oxygen, nitrogen, and sulfur (Velez et al., 2009). It has a higher energy content compared to biomass. However, the utilization of coal has caused serious environmental impact locally and globally (Li et al., 2010). Coal can be categorized based on its carbon content as shown in Table 2.3. Anthracite coals has the highest fixed carbon, followed by bituminous coal and lignite. However, lignite coal has the highest oxygen content (Mallick et al., 2017; Bowen & Irwin, 2008), which indicates that its reactivity is higher compared to other types of coal. The major differences for coal and biomass composition are in terms of fixed carbon, volatile matter, and ash. Biomass contains less ash compared to coal, while coal generally contains less volatile matter than biomass, although biomass has less fixed carbon (Mallick et al., 2017). Besides, the C, H, and S contents of coal are higher than biomass; as a consequence, there is harmful gas release from coal such as CO_2, NO_x, and SO_x, which has a negative influence to the environment (Li et al., 2010). For this work, the Adora coal from bituminous type was selected.

Table 2.3 Differences of coal types

	Anthracite	**Bituminous**	**Lignite**
Heat content (kJ/kg)	30200–35000	26000–35000	9300–19300
Moisture	<15%	2%–15%	30%–60%
Fixed carbon	85%–98%	45%–85%	25%–35%
Ash	10%–20%	3%–12%	10%–50%

Sources: Bowen & Irwin (2008)

2.4 Gasification

Gasification was first investigated by Thomas Shirley in 1659 (Stiegel & Maxwell, 2001). Gasification is the conversion of carbonaceous material into a gaseous product or synthesis gas that mainly consists of H_2 and CO, with side products of lower amounts of CO_2, H_2O, CH_4, higher hydrocarbons (C_2+), and N_2 (Paula et al., 2013). Generally, the syngas yield from gasification is influenced by various parameters including temperature, ER, gasifying agent, type of biomass, particle size, heating rate, operating pressure, catalyst addition, and reactor type (Mohammed et al., 2011). Gasification is one of the effective thermochemical conversion processes for biomass utilization, where biomass feedstock is converted into higher heating value syngas that can be used to synthesize liquid fuels and chemicals or produce heat and power (Yilmaz & Selim, 2013; Panwar et al., 2012). There are three main types of gasifier which are fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier. The gasification process is performed in the presence of a gasifying agent (for example air, pure oxygen, steam, or mixtures of these components) at elevated temperatures between 500 and 1400 °C and at atmospheric or elevated pressures up to 33 bar or 480 psi (Ciferno & Marano, 2002; Peres et al., 2013). The optimum value of ER varies between 0.2 and 0.4 in biomass gasification according to various operating parameters (Narvaez et al., 1996).

Biomass can be converted into syngas by using gasification process, alternatively, it can also be gasified with coal through co-gasification process to produce syngas (Chmielniak & Sciazko, 2003; Chen & Wu, 2009). During gasification of biomass, minor oxidation (combustion) and major pyrolysis reactions take place. The behavior of biomass pyrolysis shows drying below 125 °C; hemicellulose, cellulose, and partial lignin decomposition from 125 to 500 °C; and degradation of the remaining lignin above 500 °C. In addition, the consumption of biomass and coal for co-gasification process can improve the amount of emission for CO_2, NO_x, and SO_x due to the characteristics of biomass, which are renewable and low in contaminant (Li et al., 2010). Some synergistic effects can be expected in the co-gasification of biomass and coal caused by the high thermochemical reactivity of biomass and its high volatile matter content (Fermosa et al., 2010).

According to Paula et al. (2013), gasification process is applicable for biomass that possesses a moisture content lower than 35%. For biomass feedstock that possesses higher amounts of moisture in the range of 25%–60%, the use of these feedstock directly in the gasifier will result in a greater amount of energy loss in the overall process. It is recommended that the biomass is preheated or dried to moisture contents between 10% and 20% before it is introduced into the gasifier (Nooruddin, 2011).

The differences between coal gasification, biomass gasification, and co-gasification are shown in Table 2.4. They are evaluated based on the moisture content, volatile matter, calorific value, carbon conversion, and others. The ash, sulfur, and nitrogen contents for coal gasification are relatively high compared to biomass gasification and co-gasification. Conversely, the carbon conversion, gas yield, reactivity, volatile matter, and efficiency of coal gasification are lower than the other two types of gasification. This shows that the biomass gasification and co-gasification also have their advantages which should be given attention to as alternatives to the existing coal gasification process.

Table 2.4 Comparison on different types of gasification

Properties	**Coal gasification**	**Biomass gasification**	**Co-gasification**
Types	Fossil fuels	Renewable resource	Using clean and renewable resource
Ash	High	Low	Low
Sulfur	High	Low	Low
Nitrogen	High	Low	Low
Volatile matter	Low	High	High
Energy density	High	Low	High
Bulk density	High	Low	High
Calorific value	High	Low	High
Moisture content	Low	High	Low
Environmental pollution	Increase	Decrease	Decrease in NO_x, SO_x, volatile organic compounds
Carbon conversion	Low	High	High
Tar production	No	Yes	Low
Char production	Yes	No	Low

Source: Taba et al. (2012)

2.5 Gasification Mechanism

In gasification, the solid fuel is converted to syngas or other forms of product in gas and solid residues. The gaseous product is known as producer gas or syngas and the solid residue is known as char. The syngas produced contains different types of gas species, which may include CO, CO_2, H_2, CH_4, and inert N_2, along with light hydrocarbons (C_2–C_6) and H_2O (Abdoulmoumine et al., 2014). Three main reaction steps occur during gasification process (Chen et al., 2015). The first step involves drying and heating of biomass particles, followed by decomposition and pyrolysis of the lignin and cellulose, which break down into volatile molecules such as hydrocarbons, CO, H_2, and H_2O when the temperature is increased. Drying process occurs at temperatures of 100–200 °C where the moisture content of the biomass is reduced to less than 5%.

Pyrolysis is defined as the thermal decomposition of materials in the absence of oxygen or with the amount of oxygen supplied less than the required amount for a complete combustion reaction to occur (Balat et al., 2009). During pyrolysis, the volatile matter of the solid fuel is reduced and creates char. The char, which is the leftover from the initial solid, is then used for combustion and gasification reactions. The oxidation process occurs during gasification as the temperature is higher. This is a reaction between carbon in the biomass and oxygen in the air, forming CO_2. A large amount of heat is released with the oxidation of carbon and hydrogen. However, when the oxygen present is limited, partial oxidation of carbon may occur and generate carbon monoxide. The gases and tars undergo reactions such as water-gas shift (WGS), methanation, Boudouard, and steam-reforming reactions at higher temperature. The reactions involved during gasification are summarized in Table 2.5.

Table 2.5 The summary of gasification reaction mechanisms

Process	Reaction	Heating value	Equation	Sources
Oxidation	$C + O_2 \leftrightarrow CO_2$	$\Delta H = -393.7\ kJ/mol$	2.1	Mallick et al. (2017)
Partial oxidation	$C + \frac{1}{2}O_2 \leftrightarrow CO$	$\Delta H = -111\ kJ/mol$	2.2	Chen et al. (2013)
Steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$\Delta H = +206\ kJ/mol$	2.3	Lahijani and Zainal (2011)

Process	Reaction	Heating value	Equation	Sources
Dry reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	$\Delta H = +247.4\ kJ/mol$	2.4	Lahijani and Zainal (2011)
Water gas	$C + H_2O \leftrightarrow CO + H_2$	$\Delta H = +131\ kJ/mol$	2.5	Lahijani and Zainal (2011)
Boudouard	$C + CO_2 \leftrightarrow 2CO$	$\Delta H = +172\ kJ/mol$	2.6	Lahijani and Zainal (2011)
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H = -42\ kJ/mol$	2.7	Mallick et al. (2017)
Methanation	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H = -93.8\ kJ/mol$	2.8	Mallick et al. (2017)

2.6 Gasifier Types

Various gasification technologies and designs of reaction have been investigated by researchers to accommodate for different types of fuels. Biomass is more challenging to be gasified compared to fossil fuel due to its complex lignocellulosic structure (Samiran et al., 2016). There are three main types of gasifier that are used for the gasification process, namely entrained flow gasifier, fixed bed gasifier, and fluidized bed gasifier. The gasifiers are categorized according to various characteristics such as how the biomass is supported in the reactor vessel, the direction of flow of both the biomass and the oxidant, and the method of heat supply to the reactor.

2.6.1 Entrained Flow Gasifier

Entrained flow gasifiers, as shown in Figure 2.2, are commercially available in large scales and have high efficiency for the production of syngas (Bridgwater, 1995). It is operated at high temperature of more than 1200 °C and small particles are preferred to achieve a high conversion rate per second and could provide a high-quality tar-free syngas (Xu et al., 2014; Wang & Massoudi, 2013). The carbon conversion for this type of reactor is higher than 90% at high temperature (Qin, 2012). The residence time is very quick, around 1–5 seconds for the biomass to be completely gasified (Tremel et al., 2013). It is generally operated as an automatic thermal reactor, which means that a part of the biomass is burnt to supply enough energy for gasification reactions (Joseph et al., 2014).

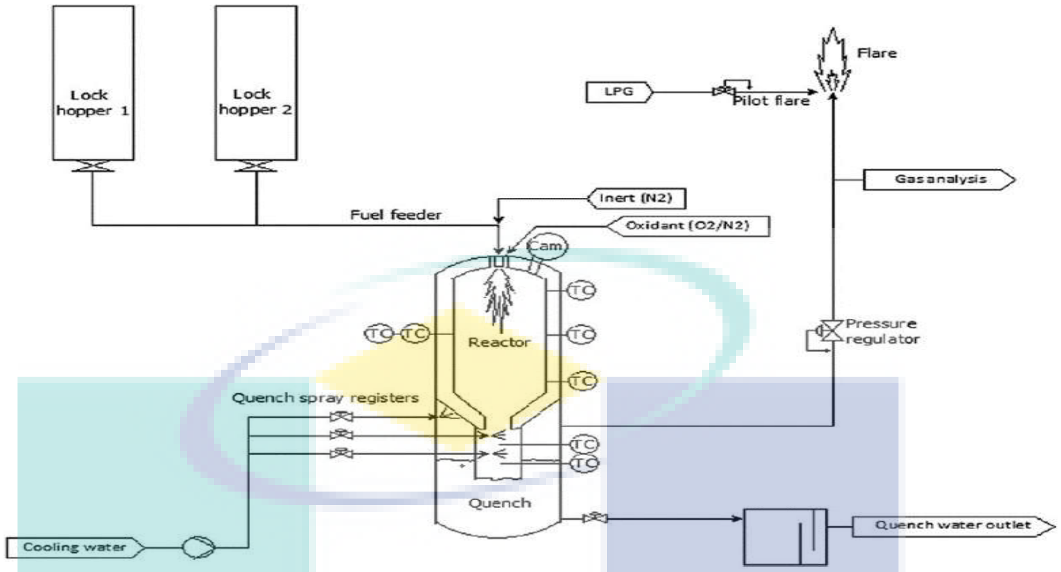


Figure 2.2 The entrained flow gasifier

Source: Ohrman et al. (2013)

High temperature ensures complete conversion of the hydrocarbon compounds resulting from pyrolysis. In this type of gasifier, pyrolysis and gasification occur simultaneously. Entrained flow gasifiers are classified as slagging or non-slagging depending on the way the ash melts and flows in the reactor. In slagging gasifiers, the ash melts in the gasifier, flows down the walls, and leaves the reactor as a liquid slag (Laurence & Ashenafi, 2012). Non-slagging entrained bed gasifiers are not as popular as slagging bed gasifiers are more fuel-flexible and it is impossible to avoid the slagging completely. Table 2.6 shows the applications for entrained flow gasification technology in industrial sectors.

Table 2.6 Entrained flow gasification technologies commercially available

Company/ Institution	Technology	Fuel	Gasification conditions	Pretreatment	References
Chemrec, Sweden	Black liquor gasification (BLG)	Concentrated black liquor	1–40 bar, 1000 °C	Integrated into pulp mill	Lindblom and Landalv (2007)
Karlsruhe Institute of Technology, Germany	GSP, modified	Bioslurry	40–80 bar, >1200 °C	Fast pyrolysis at 1 bar, 500 °C	Kolb and Zimmerlin (2014)
Linde, Germany	Carbo-V	Hot pyrolysis vapors and char powder from pretreatment	4–5 bar, >1400 °C, quenching with char to < 1000 °C	Pyrolysis at < 500 °C	Kittelmann (2014)
ThyysseenKrupp Uhde, Germany	PRENFLO	Pulverized torrefied material from wood, straw, and energy crops	25–42 bar, >1200 °C	Torrefaction	Weiland et al. (2015)

2.6.2 Fixed Bed Gasifier

In fixed bed gasifiers, the biomass is commonly fed from the top of reactor. In general, there are two common configurations for fixed bed gasifier, which are fixed bed updraft or counter current gasifier, and fixed bed downdraft or concurrent gasifier (Balat et al., 2009). The fixed bed updraft or counter current gasifier configuration is the most matured type of gasifier and has a relatively low cost to build and maintain. However, the concentration of tar in the product gas is very high (Balat et al., 2009). As such, the syngas from this type of gasifier is not suitable for direct engine usage without proper cleaning steps to reduce impurities (Brachi et al., 2014). Biomass feedstock is introduced at the top of the reactor and a gasification agent is introduced below the gasifier. The produced gas is extracted at the top of the gasifier.

The fixed bed downdraft (concurrent gasifier) has the same mechanical configuration as the updraft gasifier (Ahmad et al., 2016). In this type of reactor, the produced syngas leaves the gasifier after passing through the hot zone, enabling partial cracking of the tars that formed during gasification and giving a gas with low tar content. Because the gases leave the gasifier unit at temperatures about 900–1000 °C, the overall energy efficiency of a downdraft gasifiers is low (Kirtay, 2011). This is due to the high heat content carried over by the hot gas. The tar content of the produced gas is lower than that of an updraft gasifier but the particulate content of the gas is higher (Kirtay, 2011). Figure 2.3 illustrates a small-scale fixed bed gasifier which is usually used for biomass gasification.

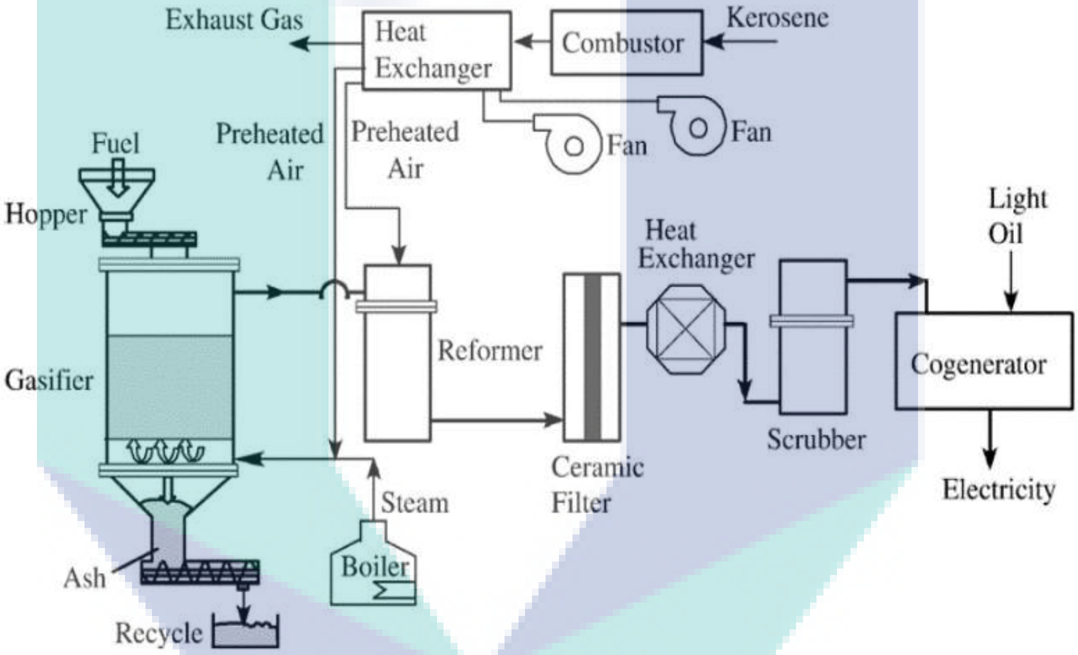
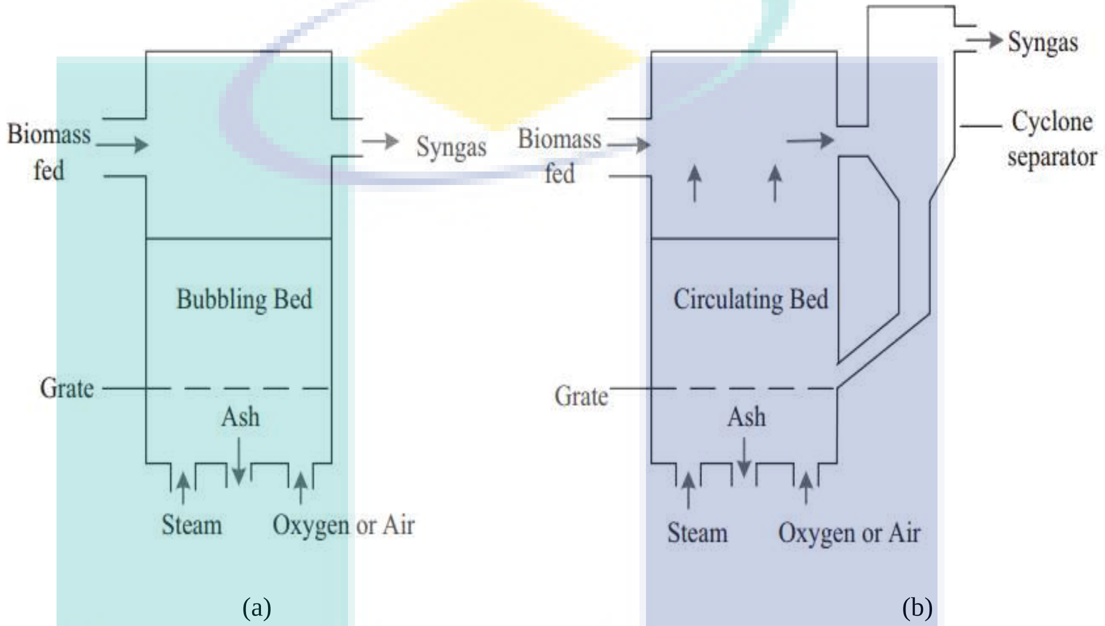


Figure 2.3 Small-scale fixed bed gasifier
Source: Wang et al. (2007)

2.6.3 Fluidized Bed Gasifier

The fluidized bed gasifiers are categorized based on their fluid dynamics and modes of heat transfer. Fluidized beds are used for a variety of fuels. This flexibility with respect to different fuels is another critical advantage of fluidized beds (Bartels et al., 2008). This type of gasifier basically operates at temperatures between 800 and 1000 °C (Ruiz et al., 2013). The feedstock is fed into the gasifier to interact and mix with the bed of solids at the set temperature (Boateng & Mtui, 2012). To produce char and gases, the process is repeated rapidly with newly arrived particles for drying and pyrolysis circulation (Ruiz et al., 2013). One of the main advantages of fluidized bed gasifier compared to fixed bed gasifier is the uniform temperature distribution attained in the gasification zone (Boateng & Mtui, 2012). There are two common types of fluidized bed gasifiers, which are the bubbling fluidized bed (Figure 2.4a) and the circulating fluidized bed (Figure 2.4b).



(a) (b)

Figure 2.4 Schematic diagrams of (a) bubbling fluidized bed and (b) circulating fluidized bed gasifier

Source: Samiran et al. (2016)

A bubbling fluidized bed usually consists of fine, inert particles of sand or alumina. At high bed temperature, biomass in a bubbling fluidized bed is pyrolyzed to form char with gaseous compounds (Ciferno & Marano, 2002). The hot bed compound will crack the char and gaseous compounds when they come into contact. As a result, the produced syngas gas will have lower tar content due to the cracking process (Udomsirichakorn et al., 2013). In a circulating fluidized bed gasifier, entrained particles in the gas exit at the top of the gasifier, are separated in a cyclone, and then are returned back to the gasifier (Ciferno & Marano, 2002). The cyclone separator eliminates the ash while the bed material and char are returned to be combusted in the reaction vessel (Samiran et al., 2016). Additionally, the content of tar in syngas can be significantly reduced due to rapid reaction, at high heat transport rate for circulating fluidized bed (Arromdee & Kuprianov, 2012).

The comparison of various types of gasifier is shown in Table 2.7. The table includes differences between entrained flow gasifier, fixed bed gasifier, and fluidized bed gasifier types. Gasifiers generally operate at high temperatures, reaching 1000 °C, such as the downdraft fixed bed gasifier and bubbling fluidized bed gasifier, and higher for entrained flow gasifiers. Entrained flow gasifier and fluidized bed gasifier are more flexible, such that they can used for various types of biomass feed for gasification. Compared to other gasifiers, entrained flow gasifiers require feed that is the smallest in size compared to the others, which is less than 0.1 mm to ensure its efficiency in producing high quality syngas. The residence time for entrained flow gasifier is also the shortest which is between 1 and 5 seconds only compared to the other gasifier types, which require longer contact time to complete the reaction. In addition, the gasifiers are able to achieve high carbon conversion, with the exception of the downdraft fixed bed gasifier and circulating fluidized bed gasifiers. Thus, for this research, the entrained flow gasifier is chosen due to its advantages compared to fixed bed gasifier and fluidized bed gasifier.

Table 2.7 Comparison of various gasifier types

Types of gasifier	Entrained flow gasifier	Fixed bed gasifier		Fluidized bed gasifier	
		Updraft	Downdraft	Bubbling bed	Circulating bed
Combustion temperature (°C)	700–1500	1500–1800	800–900	800–1000	900–1200
Feedstock type	Any biomass	Capable for biomass with high moisture	Low moisture biomass	Any biomass	Any biomass
Feedstock size (mm)	<0.1	< 2–50	10–300	<5	< 0
Residence time (s)	1–5	60	20	<55	<55
Carbon conversion (%)	90–100	Close to 100	93–96	70–100	80–90
Advantages	Various types of feedstock Syngas does not contain tar and phenolic Higher throughput and better product gas In-situ sulfur removal	Various types of feedstock Minerals remain with char/ash, decrease the uses of cyclone 99.9% of tar formed is consumed, requiring minimal cleanup		Various types of feedstock Low tar and unconverted carbon High conversion rate	
Disadvantage	Expensive construction materials and high temperature heat exchangers to cool syngas	High level of tars formation Requires feed drying to a low moisture content		Specific range of feedstock particle size Temperature gradients occur in direction of the solid flow	
References	Mondal et al. (2011), Zhou et al. (2009), Tremel et al. (2013), Samiran et al. (2016), Siedlecki et al. (2013)	Blasi et al. (2013), Cordiner et al. (2012), Samiran et al. (2016), Couto et al. (2013)		Xiao et al. (2010), Umar et al. (2014), Samiran et al. (2016), Couto et al. (2013), Udomsirichakorn et al. (2013)	

2.7 The Effect of Temperature on Biomass Gasification

One of the main parameters that affects the performance of biomass gasification process is the operating temperature. Li et al. (2009) conducted the steam gasification of EFB in a fixed bed reactor using a trimetallic catalyst at temperatures ranging between 750 and 900 °C with 50 °C increments. They found that when temperature was increased, the production for H_2 and CO_2 increased, while CO and CH_4 decreased. This is due to Le Chatelier's principle, where higher temperatures cause the reactants in exothermic reactions and favor the products in endothermic reactions. So, an increase in the operating temperature promoted the endothermic reforming reaction ($CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$), which resulted in the increase in H_2 production and decrease in CH_4 production. In addition, the WGS reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) generated CO_2 as the temperature was increased, and subsequently reduced the production of CO. This resulted in the reduction of the lower heating value (LHV) of the product gas from 11.26 to 9.13 MJ/Nm^3.

Entrained flow gasification has been used to study the influence of forest residues on oxygen stoichiometric ratio, gasifier pressure, and fuel particle size. An increase in oxygen stoichiometric ratio resulted in an increase in temperature between 150 to 200 °C. The experimentally determined syngas yield of CO reached the maximum at an oxygen stoichiometric ratio of 0.425, corresponding to a process temperature of approximately 1400 °C. Meanwhile, when the oxygen stoichiometric ratio was below 0.425, the process temperature was lowered and CH_4 yield became significant. The carbon conversion decreased from 0.95 to 0.8 as the oxygen stoichiometric ratio decreased from 0.3 to 0.25. This was due to incomplete char gasification and the production of soot. The CGE achieved a maximum of 0.70 when the oxygen stoichiometric ratio was at 0.35 (Weiland et al., 2015).

The analysis on EFB gasification using a bench-scale fluidized bed gasifier has also been studied. As the temperature was increased from 700 to 1000 °C, H_2 and CH_4 also increased while CO_2 content decreased. During the initial temperature increase to 800 °C, the CO content increased before slightly decreasing at temperature 900 °C and increased again when temperature was increased to 1000 °C. At high temperature, the gas species produced from biomass at pyrolysis zone has been suggested to possibly undergo secondary reactions such as tar cracking and shifts reaction, leading to the generation of more incondensable gases including H_2. Thus, as temperature was increased from 700 to 1000 °C, the total yield of gaseous products increased significantly. In terms of increasing H_2 production, water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) and steam reforming ($CH_4 + H_2O \leftrightarrow CO + 3H_2$) were the main reactions for EFB gasification at atmospheric pressure and temperature between 700 and 1000 °C. From the product analysis, the higher temperature at 1000 °C is concluded to be favorable for thermal cracking of tar and shift reactions, with enhanced syngas production (Mohammed et al., 2011).

Another research on the gasification of lignocellulose biomass in fluidized bed gasifier has confirmed that the bed temperature is one of the most important operation parameters which affects the performance of the gasification process. Increasing the gasification temperature reduces the gas heating value, as high temperature improves biomass combustion which consequently results in more CO_2 and N_2 production and lowers the LHV. On the other hand, high bed temperature improves carbon conversion, steam cracking, and reforming of tars, which resulted in less char and tar formation and high gas yields (Alauddin et al., 2010). Experiments were performed in an entrained flow gasifier on sawdust. The effect of reaction temperature and ER on the producer gas composition, LHV, carbon conversion, and CGE were investigated. When the reaction temperature was increased, the concentration of CO decreased, while the concentrations of H_2 and CO_2 increased. When the reaction temperature was 800 °C, the concentrations of CH_4 and C_2H_4 reached their maximum value. The maximum for LHV of the produced gas was 6.00 MJ/Nm^3, carbon conversion and CGE reached their maximum values at 92.8% and 66.7%, respectively, at reaction temperature 800 °C. The optimal reaction temperature and ER are considered to be 800 °C and 0.28, respectively, where the low heating value of the produced gas, carbon conversion, and cold gas efficiency achieve their maximum values (Zhao et al., 2010).

The investigation of EFB biochar gasification in a fluidized bed using air has determined that as the temperature increases, the gas yields of H_2 and CO increase, while CO_2 and CH_4 decrease. This is in accordance with the Le Chatelier's principle, where higher temperatures favor the reactants in the exothermic reactions (WGS and Boudouard) and the products in the endothermic reaction (steam reforming). It influences the increase in H_2 and CO production, which are the most important gases in syngas production because the reactions are shifted towards the reactant side at high temperatures. CH_4 forms H_2 and CO as the temperature increases, thus increases the concentrations of H_2 and CO (Salleh et al., 2010). Experimental works on Karanja Press Seed Cake has been carried out in an entrained flow gasifier. The effects of temperature, ER, steam-to-biomass ratio, and particle size were investigated to determine the syngas composition, LHV, CGE, and carbon conversion. The CO and H_2 significantly increased whereas CO_2 and CH_4 content decreased with an increase in the gasification temperature. This can be explained by CO_2 being mainly generated from the decomposition of carboxyl groups at low temperature (below 800 °C) with oxidation and water-gas shift reactions. The CH_4 concentration decreased with a rise in temperature, which might be due to cracking reaction. CGE increased with an increase in the gasification temperature. The highest value of CGE up to ~90% was obtained at 1100 °C (Dhanavath et al., 2018).

H_2 production only increases up to an optimum temperature, whereas further increase in the temperature would be detrimental. This is due to the WGS reaction, which is sensitive to temperature increase and has the tendency to shift the reaction towards the reactants according to Le Chatelier’s principle. Another similar finding through a study in fluidized bed gasification of rise husk also found that H_2 and CO concentrations increased with a rise in the operating temperature while the concentrations of CH_4 and CO_2 decreased. At 750 °C, an increase in the S/B ratio resulted in the most optimum H_2 production as steam is the major source of H_2 during steam gasification. This subsequently contributed to the higher carbon conversion and higher gas yield but lower higher heating value (HHV) (Karmakar and Datta, 2011).

In addition, researchers have performed experiments on the effect of temperature in a bubbling fluidized bed gasifier, using larch wood as the feed material. Although the temperature range that they studied was rather small, which was between 650 to 750 °C, its effect on the gas yield and composition, carbon distribution of products, and cold gas efficiency (CGE) was still significant. The carbon in the char product and total tar production decreased greatly as gasification temperature was increased. In turn, the carbon content in the product gas increased. As they used steam as the gasification medium, high H_2 production was determined, simultaneously producing the less desirable products such as CO_2 and tars. A lower carbon content from char and tar in the bed material from steam gasification were distinguished which may be attributed to the char and tar decompositions (Weerachanchai et al., 2009). Similarly, when the temperature was increased, H_2 production increased until the temperature reached 700 °C due to the thermal decomposition of CH_4 into H_2, although further increase in temperature increased the CO production, which corresponded to the decrease in CO_2 production (Dillibabu & Natarajan, 2014).

Biomass gasification on wood and straw using entrained flow gasifier has also been investigated. The effect of reaction temperature, steam/carbon molar ratio, and excess air ratio were investigated to determine the product gas composition. As the temperature increased from 1000 to 1350 °C, the yield of gas product increased by 72%. Moreover, the H_2/CO molar ratio of syngas was close to 1 when the temperature was above 1200 °C. When the excess air ratio rose from 0.25 to 0.5, there was no significant change in producer gas yield, however, the yields of H_2, CO, and soot decreased, the CO_2 yield increased, and the molar ratio of H_2/CO decreased (Qin et al., 2012). Gasification of bamboo has been investigated using entrained flow gasifier. The influences of ER and oxygen/fuel ratio on syngas formation, carbon conversion, and CGE was determined. When the O/F was at 0.9, most atomic hydrogen is transformed to H_2O, therefore, the concentration of H_2 became lower. Besides, the insufficient oxygen supplied in the gasification environment generated CO. The carbon conversion and CGE for bamboo gasification were 92.2 and 29.0%, respectively. The value of the CGE was determined from the heating values and mass fractions of CO, H_2, and CH_4. The high CC and low CGE resulting from raw biomass gasification are attributed to the high concentrations of CO_2 and H_2O, as well as to the low concentrations of CO and H_2 in the product gas (Chen et al., 2013).

2.8 The Effect of ER on Biomass Gasification

ER is another crucial parameter that dictates the performance of a gasification process, specifically in the syngas production. The effects of ER and gasifying agents on some important characteristics of a gasification process, such gas composition, syngas ratio, and LHV using a fluidized bed reactor have been investigated. When ER was increased, the H_2, CO, and CH_4 concentrations decreased. Increasing the ER from 0.1 to 0.5 reduced the LHV of the product gas and it was not influenced by the type of gasifying agents used. This is due to the high degree of combustion occurring at high ER, when more oxygen was supplied into the gasifier to induce complete combustion, hence increasing CO_2 concentration, instead of the desired combustible gases such as CH_4, H_2, and CO. The LHV of the syngas derived was higher when O_2 was used compared to when air was used as the gasifying agent at the same ER. This may be attributed to the dilution of the syngas by N_2 presence in air (Zheng et al., 2016).

Experimental works on Karanja Press Seed Cake have been carried out in an entrained flow gasifier. The effects of temperature, ER, steam-to-biomass ratio, and particle size were investigated to determine the syngas composition, LHV, CGE, and carbon conversion. As the ER increased from 0.1 to 0.3, the production of CO and H_2 increased. The maximum production was achieved at ER = 0.3 before decreasing rapidly. The rapid decrease in the CO content at higher ER can be explained by the presence of higher amount of O_2 which favored CO_2 formation over CO. CH_4 also decreased slightly at ER > 0.3. However, compared to CO and H_2, the reduction in CH_4 with the increase in ER was not significant. This might be due to lower equilibrium partial pressure and higher reactivity of CO and H_2 compared to CH_4. Moreover, the LHV of syngas increased with ER up to 0.3. Then, as the ER exceeded 0.3, the LHV started declining. The maximum value of LHV of 12 MJ/Nm^3 was obtained at 1000 °C at the ER of 0.3. The optimum ER value considered for oxygen–steam entrained flow gasification is 0.3 (Dhanavath et al., 2018).

Another exploration on the effect of ER has been performed for a fixed bed gasifier using dairy biomass. Using enriched air resulted in the presence of nitrogen in syngas, which lowers the heating value of gases due to the dilution effect. Similarly, the production of CO_2 increased with an increase in ER, due to higher oxygen concentration in the gasification medium. It was accompanied by a decrease in CO production and subsequent increase in the production of H_2. On the other hand, the amount of H_2 produced increased with the introduction of steam into the gasification reactor, resulting in the production of syngas with higher HHV (Thanapal et al., 2012). Other experiments were performed in an entrained flow gasifier on sawdust. The effects of reaction temperature and ER on the producer gas composition, LHV, carbon conversion, and CGE were investigated. When the ER was increased from 0.22 to 0.34, the concentration of H_2 decreased from 14.61% to 10.23%, CO decreased from 25.71% to 21.46%, CH_4 decreased from 2.45% to 0.87%, and C_2H_4 decreased from 0.34% to 0.09%. Meanwhile, the concentration of CO_2 increased slowly from 11.74% to 12.34%. Besides, the LHV of producer gas decreased from 6.67 to 4.65 MJ/Nm3 at 800 °C and from 5.9 to 4.17 MJ/Nm3 at 1000 °C, respectively, when the ER was increased. Also, when the ER was increased from 0.22 to 0.28, the CGE increased from 62.8% to 66.7%, and then decreased to 56% with further increase of the ER to 0.34 (Zhao et al., 2010).

The effects of parameters in gasification such as ER, gasification temperature, fuel type and its moisture content, and gasifying agent have been investigated. Pine sawdust was gasified at 800 °C to study the effects of various parameters on gasification performance. Increasing the ER leads to decreasing H_2 content. This is possibly because of further oxidation of H_2, due to the presence of more oxygen in the system. CO content in syngas increased when ER value was increased then decreased; meanwhile, CO_2 content in syngas showed the inverse trend. N_2 content in the produced syngas increased due to the increase in air introduced to the reactor. Also, with the increase in ER, temperature increased. This suggests the occurrence of exothermic combustion reaction due to the presence of more oxygen in the system. At lower ER, as moisture content increased, CGE decreased. On the other hand, when ER was higher, the CGE remained constant for different moisture contents. The maximum efficiency for higher temperature was produced at lower ER value, hence the researchers concluded that lower ER should be maintained for a more efficient gasification process (Ghassemi & Shahsavan-Markadeh, 2013). Gasification of bamboo has been investigated using entrained flow gasifier. The influences of ER and oxygen/fuel ratio on syngas formation, carbon conversion, and CGE were determined. An increase in ER led to the growth of the carbon conversion, resulting from excess oxygen supplied to reaction. The optimum ER value for gasification of raw bamboo was 0.692 where the maximum value of CGE was 28.98%. However, as ER exceeded the most appropriate values, the CGE decayed, implying that overoxidation of fuel occurred, whereby the syngas formation decreased (Chen et al., 2013).

Another study on the effect of ER on the air gasification of pine also found that when the ER was increased, the concentrations of CO and H_2 decreased while CO_2 increased due to complete oxidation (Abdoulmoumine et al., 2014). Mohammed et al. (2011) gasified EFB in a fluidized bed bench scale gasifier. They also found that when ER was increased, the product gas quality decreased due to the increase in the oxidation reaction. If the ER value is too high, the concentrations of H_2 and CO are lowered. When ER was varied from 0.15 to 0.35, the H_2 content increased to the maximum value at ER of 0.25, while the CO_2 content increased steadily. On the other hand, CH_4 and CO decreased with increasing ER. This can be explained by the fact that oxidation reactions are always strong, and the ER increase influenced the oxidation reactions of combustible product gases, which resulted in more CO_2 produced, hence the steady increase. Skoulou et al. (2008) has established that at low ER value of 0.2, the concentration of CO was higher compared to at higher ER values. This detrimental effect was also thought to be due to the complete oxidation reaction with more oxygen availability, along with the N_2 dilution effect.

Most of the previous researchers focused on fixed bed gasifier and fluidized bed gasifier for their biomass gasification. These researchers used mostly agricultural biomass or forest residues and a handful of them used palm oil waste. Less attention has been given for the application of entrained flow gasifiers especially in biomass co-gasification, although the advantages of entrained flow gasifier compared to others have been proven by previous researchers. The entrained flow gasifier gives higher carbon conversion production, produces low tar formation, and has a shorter reaction time. Besides, the utilization of entrained flow gasifier in agricultural and forestry residue in Malaysia can still be explored due to various types of biomass that can be found in Malaysia especially. The summary for the previous studies on biomass gasification is shown in Table 2.8.

Table 2.8 Summary of previous studies on biomass gasification

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Fixed bed	EFB	Temperature S/B Biomass particle size	Gas yield LHV	With temperature increase, H_2 and CO_2 increased, CO and CH_4 decreased, LHV decreased. With S/B increase, gas yield and H_2 yield increased while CO, CH_4, C_2 hydrocarbon, and LHV decreased. With smaller particle size, H_2 and CO increased while CH_4, CO, C_2H_4, and LHV decreased.	Li et al. (2009)
Fluidized bed	Pine sawdust	ER O_2-enriched air Fuel type Moisture content Process temperature	CGE HHV of syngas	With ER increase, CO increased while CO_2 and H_2 decreased. With O/A ratio increase, HHV of syngas increased. With larger H/C ratio, increased CGE and maximum efficiency occured at lower ER. With lower moisture content, higher HHV. With higher temperature, maximum CGE was obtained in lower ER.	Ghassemi and Shahsavan-Markadeh (2013)
Entrained flow	Sawdust	Reaction temperature ER	Product gases LHV Carbon conversion CGE	With temperature increase, concentration of CO decreased, concentrations of H_2 and CO_2 increased. At temperature 800 °C, concentrations of CH_4 and C_2H_4 were at maximum value. When ER is increased, the concentration of H_2, CO, CH_4, and C_2H_4 decreased while, the concentration of CO_2 increased slowly. When ER is increased, LHV of producer gas decreased, CGE increased then decreased further with the increase of the ER to 0.34. The optimal reaction temperature and ER were 800 °C and 0.28, respectively.	Zhao et al. (2010)

Table 2.8 Continued

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Fluidized bed	Lignocellulosic biomass	Bed material Bed temperature ER S/B Biomass particle size	Producer gas composition LHV Tar and char content Gas yield Carbon conversion CGE	Dolomite is a catalyst which removes heavy hydrocarbons from the gas stream and decreases agglomeration. High temperature improved product formation in endothermic reactions whereas they favored reactants in exothermic reactions. Increasing the ER decreased LHV of the producer gas. Introduction of steam to the system improved the gas yield, LHV, and carbon conversion efficiency. The yield and composition of the producer gas improved while using small particle biomass.	Alauddin et al. (2010)
Entrained flow	Forest residue	Oxygen ratio Gasifier pressure Fuel particle size	Gas yield	CO reached the maximum at oxygen stoichiometric ratio of 0.425, at process temperature 1400 °C. When below 0.425, the process temperature was lower and CH_4 yield became significant. The carbon conversion decreased as the oxygen stoichiometric ratio decreased. The CGE achieved the maximum of 0.70 when the oxygen stoichiometric ratio was at 0.35.	Weiland et al. (2015)
Fluidized bed	Pine sawdust	Reaction temperature S/B ER Biomass particle size	Gas composition Gas yield LHV Carbon conversion efficiency	With temperature increase, H_2 increased, CH_4 and CO decreased, and carbon conversion efficiency increased. Higher ER caused gas quality to degrade but accelerated gasification. Introduction of steam within a range improved gas yield, LHV, and carbon conversion efficiency. Smaller biomass particle size gives higher gas yield.	Lv et al. (2004)

Table 2.8 Continued

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Fluidized bed	Pine wood	Temperature ER	Primary gases Gas contaminants	With temperature increase, CO and H_2 increased, CO_2 and CH_4 decreased, tar yield decreased, and NH_3 and HCN decreased. As ER is increased, CO and H_2 decreased while CO_2 increased; CH_4, C_2H_2, and C_2H_4 not significantly affected; and tar formation decreased.	Abdoulmoumine et al. (2014)
Entrained flow	Coal-water mixture	Temperature ER Air/O_2 ratio	Syngas composition Carbon conversion CGE	H_2 and CO increased while CO_2 and CH_4 decreased with increasing temperature. Carbon conversion increased with increasing temperature. With an ER increase from 0.26 to 0.41, the amount of H_2, CO, and CO_2 increased while CH_4 decreased. The carbon conversion recorded 60.2% at an ER of 0.41. Increasing H_2 and CO caused an increase in CGE to 40.1%.	Oh et al. (2018)
Fluidized bed	EFB	Temperature Particle size ER	Gas yield	With temperature increase, H_2 and CH_4 increased, CO_2 decreased, total gas yield increased. With ER increase, product gas decreased. Optimum ER was at 0.25 where H_2, CH_4, and CO increased then decreased, while CO_2 increased steadily.	Mohammed et al. (2011)
Fluidized bed	Larch wood	Bed material Gasification temperature Gasifying agents	Gas yield CGE	Calcined limestone and calcined waste concrete gave high content of H_2 and CO_2, while silica sand gave high content of CO. With temperature increase, gas yield and CGE increased while tar and char content decreased. Amount of total gas produced from steam gasification was higher than pyrolysis process (pure N_2).	Weerachanchai et al. (2009)

Table 2.8 Continued

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Entrained flow	Karanja Press Seed Cake	Temperature ER Steam-to-biomass ratio Particle size	Syngas composition Carbon conversion LHV CGE	CO and H_2 significantly increased whereas CO_2 and CH_4 content decreased with increase in the gasification temperature. CGE increased with increase in the gasification temperature up to ~90% can be obtained for 1100 °C. With ER increase, CO and H_2 increased and achieved the maximum when ER = 0.3, then decreased rapidly. CH_4 decreased slightly at ER > 0.3. LHV of syngas increased with ER up to a value of 0.3. As the ER exceeded 0.3, LHV started declining. The optimum ER value was 0.3	Dhanavath et al. (2018)
Entrained flow	Rusk husk, sawdust, camphor wood	Temperature Residence time Oxygen/ biomass ratio	Carbon conversion CGE	The H_2 and CO contents increased with temperature, whilst CO_2 and CH_4 decreased CGE increased as temperature increased from 1000 to 1400 °C.	Zhou et al. (2009)
Fixed bed	Dairy manure	Enriched air mixture ER S/B	HHV Gas composition Gasification efficiency	With ER increase, the peak temperature decreased, favored production of CO, CO_2 increased while CO decreased. Amount of hydrogen produced increased with the introduction of steam. For both air gasification and enriched-air gasification, there was a decrease in HHV with ER. At higher ER, gasification efficiency was low.	Thanapal et al. (2011)

Table 2.8 Continued

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Entrained flow	Wood straw	Temperature Steam/carbon ratio Excess air ratio	Gas product yield	With temperature increase, the yield of gas product increased by 72%. H_2/CO molar ratio of syngas was close to 1 when the temperature was above 1200 °C. As excess air ratio rose, there was no significant change in producer gas yield, however, the yields of H_2, CO, and soot decreased, the CO_2 yield increased, and the molar ratio of H_2/CO decreased.	Qin et al. (2012)
-	Coir pith	Temperature ER	Gas composition Heating value of product gas	With increased temperature, H_2 and CO increased, and CO_2 decreased. Maximum calorific value was obtained at ER = 0.3 and temperature = 800 °C.	Dillibabu and Natarajan et al. (2014)
Fluidized bed	Rice husk	Reactor temperature S/B	Gas composition Gas yield Carbon conversion	With increased temperature, H_2 and CO concentration increased while CO_2 and CH_4 decreased. With increased S/B, H_2 and CO_2 concentrations gradually increased while CO and CH_4 decreased. Increase in S/B resulted in higher production of H_2 but decrease in HHV. Higher temperature and S/B increased carbon conversion.	Karmakar and Datta (2011)
Entrained Flow	Grapevine pruning, sawdust waste, and marc of grape	Biomass particle size Space residence time Temperature	Gas composition H_2/CO ratio	As temperature and space time increased, the content of H_2 and CO increased Thus, increase producer gas LHV and CGE H_2/CO decreased when residence time increased at temperature lower than 1000 °C and rose at higher temperature.	Hernandez et al. (2010)

Table 2.8 Continued

Types of Gasifier	Biomass	Operating Parameters	Investigated Parameters	Findings	Reference
Fluidized bed	Bio-oil from rice husk	ER Gasifying agent	Gas composition H_2/CO LHV Tar amount CGE	With ER increase, H_2, CO, and CH_4 decreased while CO_2 increased. H_2/CO increased when ER increased. With increase in ER, LHV and tar amount decreased. Maximum CGE was at ER value of 0.3.	Zheng et al. (2016)
Entrained flow	Bamboo	ER Oxygen/fuel ratio on	Syngas formation Carbon conversion CGE	O/F at 0.9, most atomic hydrogen was transformed to H_2O, therefore the concentration of H_2 became lower. At low ER, CO was generated. The carbon conversion and CGE were 92.2 and 29.0%, respectively. Optimum ER value was at 0.692 where the maximum value of CGE	Chen et al. (2013)
Fluidized bed	Olive kernel	Temperature ER	Gas quality LHV H_2/CO	As temperature and ER increased, CO increased. H_2 production at lower gasification temperature and ER. At low ER and high temperature, CH_4 production was favored. Higher ER caused higher LHV and H_2/CO.	Skoulou et al. (2008)

2.9 Previous Work on Co-Gasification of Coal and Biomass

For co-gasification process, the main parameters that affect the performance are biomass ratio and temperature. Fluidized bed co-gasification of coal and olive oil to enhance syngas production and improve its composition has been studied. In co-gasification, the HHV values were higher than in pure coal gasification because of higher amounts of gases having larger HHV were produced and high biomass contents. In co-gasification, lower HHV is increased with the rise in temperature due to an increase in H_2 production. They found that the obtained HHV decreased due to a reduction in the contents of CH_4 and hydrocarbons, while the CGE increased with an increase in temperature because of the increase in gas yield and heating value of the produced gas. However, the CGE in biomass gasification was higher than in coal gasification because of the higher yield in the gaseous product during biomass gasification. An increase in temperature caused a reduction in tar and char formation during gasification. Tar yields were higher in biomass gasification than in coal gasification at the same temperature. In co-gasification, tar yield decreased with the increase in temperature due to cracking and reforming of tars. Char yield decreased by reducing the amounts of coal and increasing temperature in co-gasification. Char produced in co-gasification was higher than in biomass gasification, though less than in coal gasification (Andre et al., 2005).

Coal/bio-oil slurry has been investigated using entrained flow gasifier at various temperatures, steam/carbon ratios, and coal concentrations to identify the effect on syngas yield and carbon conversion. The H_2 and CO content increased with increasing while CO_2 and CH_4 content decreased. The increased H_2 and CO content might be attributed to the promotion of methane cracking reaction and the inhibition of water-gas shift reaction at high gasification temperature. When temperature was increased to 1300 °C, the syngas components were similar except for CH_4 content. At 1400 °C, CH_4 was not detected in syngas and its components were similar with those in equilibrium. The carbon conversion increased from 85% to 99% when the temperature was increased from 1200 to 1400 °C. As the steam/carbon ratio increased from 0.53 to 0.5, the molar ratio H_2/CO increased from 1.36 to 3.20. The increased H_2/CO is owing to elevated H_2 content and reduced CO content. The significant change in gas products was probably caused by the water-gas shift reaction. High steam/carbon ratio promotes conversion of CO to produce H_2 and CO_2, and causes a decrease in CO content. In addition, at steam/carbon ratio of 5, the carbon conversion to gas reached 96%, and it was 20% higher than that at steam/carbon ratio of 0.5 (Feng et al., 2016).

The gasification of four coals of different ranks, using steam/oxygen mixtures as the gasifying agent, at atmospheric and elevated pressure in a fixed bed reactor fitted with a solid feeding system in continuous mode has been investigated. From the study, the syngas produced, which are H_2 and CO, were always higher at atmospheric pressure than at 15 atm, regardless of the coal rank, while the production of CO_2 and CH_4 were favored at elevated pressure. This is due to the shift in the equilibrium gas phase reactions to the side which has fewer moles of gas. At atmospheric pressure, a higher and faster release of volatile matter occurs, leading to a reduction in the amount of char produced. Besides that, the productions of the oxygenated species such as CO and CO_2 were increased with increased coal carbon content. This is because the main gases produced during gasification depend on the carbon content of the fuels, and the potential to produce these gases increases with the carbon content. Moreover, the production of H_2 and CO increased with the addition of biomass contents. A slight increase in CO_2 production was observed. There was an increase in the gas production as biomass fuels are more reactive than coal. The carbon conversion of the coal–biomass blends and the gas yields were higher than the individual coal gasification. An increase in CGE was due to the higher gas yield and its higher HHV. Thus, the synergistic effect may occur at the highest HHV and CGE value due the blending of coal and biomass (Fermosa et al., 2010).

Performance evaluation on co-gasification of bituminous coal and wheat straw has been conducted in an entrained flow gasifier. The effects of gasification temperature, biomass mixing ratio, and oxygen/carbon ratio on the gas production were analyzed. When the mass ratio of the wheat straw increased from 0.25 to 0.75, the gasification activation energy decreased from 193.58 to 129.57 kJ/mol. When the gasification temperature was increased, the CGE increased, moreover, the H_2 and CO content also increased. However, the opposite trend was shown for CO_2 and CH_4. In addition, the contentd of H_2 and CO increased as the mass ratio of wheat straw increased. At 50% of biomass ratio, the synergistic effect was observed. The optimum operating parameter was achieved at oxygen-fuel ratio of 0.45 and gasification temperature of 1300 °C, (Wu et al., 2017). The co-gasification of coal and biomass in a fluidized bed gasifier at atmospheric pressure has also been investigated. The effect of temperature on gasification, steam/fuel ratio, and tar deposition were investigated in this research to determine the syngas product concentration. At higher temperature, H_2 and CO_2 decreased while there was an increase in CO production. These were the results from the WGS reaction which can be less influential than the Boudouard and the water-gas reactions. In addition, methanation was probably the influencing reaction for the decreasing of H_2 concentration (Velez et al., 2009).

The experiment on the effect of ER in the range of 0.31–0.47 for the co-gasification of biomass and coal in a fluidized bed reactor, as well as steam/carbon ratio, has also been conducted. When the bed temperature was increased from 948 to 1026 °C, more oxygen was introduced into the gasifier which enhanced the combustion as ER increased. Thus, the concentrations of H_2 and CO in the produced syngas decreased due to the oxidation of H_2 and CO (Li et al., 2009). Co-gasified woody biomass and coal with air and steam using fixed bed gasifier has been investigated. The experiment was done at 1173 K and the reaction time was 1 h. As the biomass ratio increased, the gas conversion increased whereas conversion of tar and char decreased. The conversion to tar was less at higher biomass ratio due to the air–fuel ratio was relatively high. For the syngas production, H_2 composition decreased while CO_2, CO, CH_4, and hydrocarbon increased as biomass ratio was increased. In addition, H_2/CO and H_2/CO_2 molar ratio in product gas decreased while CGE increased with increasing biomass ratio (Kumabe et al., 2007).

An entrained-flow gasifier of 1 T/D scale was used with the coal water mixture as feedstock. The effects of temperature, ER, and air/O_2 ratio were investigated to determine the syngas composition, CGE, and carbon conversion. As the ER was increased from 0.26 to 0.41, the amount of H_2, CO, and CO_2 increased while CH_4 decreased. The carbon conversion increased due to the increase in CO and CO_2, recording 60.2% at an ER of 0.41. Increasing H_2 and CO caused CGE to increase to 40.1%. The concentration of CO increased with ER and reached 29.61% at an ER of 0.62. H_2 content decreased after increasing to 32.14% at an ER of 0.53. Carbon conversion rose continuously due to changes in the concentrations of CO and CO_2, reaching 96.1% at an ER of 0.62. The CGE reached 52.1% with an ER of 0.53, followed by a gradual decrease. CGE increased up to an ER of 0.53 due to the increase in

H_2 and CO, but then gradually decreased with decreasing H_2 and increasing CO_2. The H_2 and CO composition significantly increased while CO_2 and CH_4 decreased with the increase in gasification temperature. The increase in CO and decrease in CO_2 are expected to be the effect of the Boudouard reaction. The amount of CO_2 slightly decreased as the temperature increased above 1003 °C. Carbon conversion was 59.1% at 970 °C and continued to rise to 95.5% with increasing temperature. The increase in carbon conversion was due to the increase in CO content. In addition, the CGE increased with rising gasification temperature until it reached the maximum value at 61% (Oh et al., 2018).

Utilization of coal with biomass has become one of the technologies of choice among researchers due to its favorable output and positive impact on environmental pollution. Co-gasification of biomass with coal can reduce the emission of harmful gases during the reaction such as CO_2, NO_x, and SO_x due to the properties of biomass, thus reducing air pollution. Many of the previous studies on the co-gasification of coal and biomass were conducted based on the fixed bed and fluidized bed gasifiers. Less attention has been given to the co-gasification although recent studies have proved that utilization of biomass and coal increases the syngas production. In addition, higher HHV and CGE can also be improved from the co-gasification process.

The summary of previous studies on co-gasification process is shown in Table 2.9.

Table 2.9 Summary of previous co-gasification studies

Types of Gasifier	Materials	Operating Parameters	Investigated Parameters	Findings	Reference
Fluidized bed	Coal and olive oil	Temperature Biomass content	Gas composition HHV CGE Tar content	With temperature increase, H_2 increased while CH_4 decreased, LHV and CGE increased, tar and char formation decreased, carbon conversion and gas yield increased. With biomass content increase, H_2, CO, and CGE increased.	Andre et al. (2005)
Entrained flow	Bituminous coal and wheat straw	Temperature Biomass ratio Oxygen/carbon ratio	Gas products Activation energy CGE	With mass ratio increase, the gasification activation energy decreased from 193.58 to 129.57 kJ/mol. With gasification temperature increase, CGE, H_2, and CO content increased, CO_2 and CH_4 decreased. The content of H_2 and CO increased as the mass ratio of wheat straw increased. At 50% of biomass ratio, the synergistic effect was observed.	Wu et al. (2017)
Fixed bed	Coal with biomass and petroleum coke	Gasification pressure Biomass ratio	Gas composition Carbon conversion CGE	With increase in pressure, H_2, CO, and carbon conversion decreased. With biomass ratio increase, H_2 and CO increased while CO_2 decreased, H_2/CO decreased, cold gas efficiency and carbon conversion increased.	Fermosa et al. (2010)
Entrained flow	Biomass Coal-coke mixture	Fuel/air ratio Temperature Biomass content	Gas composition	As temperature increased, synergies increasingly reduced CO content, gas heating value and CGE almost linear at high temperature As temperature increased, H_2/CO, CO/CO_2 and H_2/CO_2 ratios increased	Hernandez et al. (2010)

Table 2.9 Continued

Types of Gasifier	**Materials**	**Operating Parameters**	**Investigated Parameters**	**Findings**	**Reference**
Fluidized bed	Coal and biomass	ER Steam/carbon ratio, Fs/Fc Biomass/coal ratio	Gas composition Bed temperature	With increase in bed temperature increased, H_2 and CO decreased, causing decrease in C/O ratio. As Fs/Fc increased, bed temperature and CO/H_2 decreased. With biomass ratio increase, bed temperature and H_2 increased while CO decreased.	Li et al. (2009)
Fluidized bed	Coal and biomass	Temperature Steam/fuel ratio	Gas composition Tar Energy efficiency	At higher temperature, H_2 and CO_2 decreased while CO increased. Tar accumulation can be reduced by maintaining a temperature high enough that avoids tar formation.	Vélez et al. (2009)

2.10 Summary

Biomass is a renewable energy resource and an environmentally friendly fuel which contains less sulfur and ash besides having higher amount of volatile matter than coal. In Malaysia, biomass (EFB, OPF, and Kempas) is widely available, easy to obtain, and has low cost. So, due to the abundance of biomass in Malaysia, it is suitable to be used as feedstock in biomass gasification. Besides that, biomass gasification can be said as a cleaner technology which produces lower quantities of CO_2, NO_x, and SO_x gases that are harmful to the environment (Taba et al., 2012). This is due to the properties of biomass that has low ash and less fixed carbon compared to coal. Furthermore, utilization of entrained flow gasifier for biomass gasification improves the syngas production.

Co-gasification gives better syngas production compared to using biomass alone. However, the suitable biomass–coal ratio needs to be identified to obtain the maximum production of product syngas. Moreover, gasification using entrained flow gasifier increases the carbon conversion, lowers the tar content, and shortens the reaction time. In addition, the co-gasification process also reduces the pollution caused by using only coal in coal gasification process. Co-gasification of coal and biomass in an entrained flow gasifier can be explored more due to lack of research related to this nowadays.

Thus, using co-gasification and biomass gasification can reduce the amount of pollution produced during the gasification process. Recently, there has been significant amount of research works for co-gasification and biomass gasification using various types of gasifier at different operating conditions. Therefore, in this work, the use of entrained flow gasifier technology is being highlighted due to its advantages mentioned previously.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the materials and methods used for the experimental work done to achieve the objectives of this study are presented. The sample preparation, design of the experimental equipment, set up, and experimental procedures are all described in the following sections. The details for every equipment are briefed including model, brand, and limitation of the equipment and other analyses. Figure 3.1 shows the overall methodology for this study which includes the preparation of materials, experimental setup and procedure, and analysis of product.

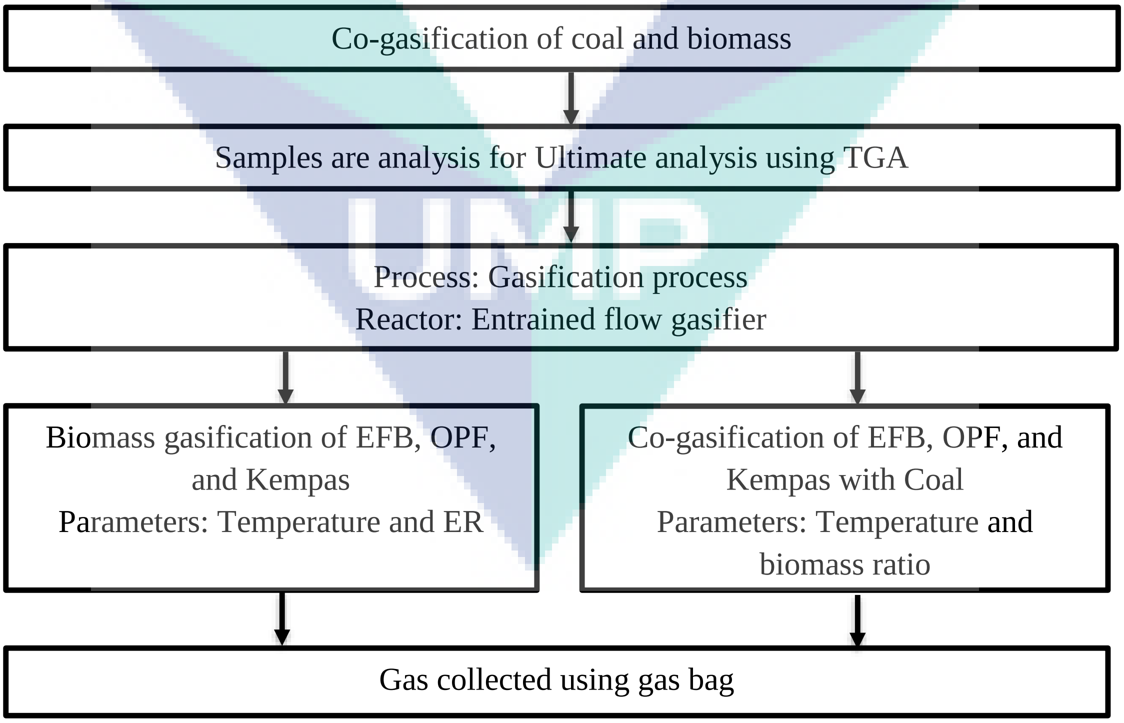


Figure 3.1 The overall methodology for this study

3.2 Materials

The raw materials used in this research were EFB, OPF, Kempas (*Koompassia malaccensis*), and Adaro coal. EFB and OPF were collected from Kilang Sawit LCSB Lepar Hilir, Kuantan and Kempas waste was collected from Kilang Kayu Gambang, Kuantan. Meanwhile, the coal used in this work was obtained from TNB Research Bangi. They are from Adaro and are being used in Sultan Salahuddin Abdul Aziz Power Station, Selangor, Malaysia. Nitrogen gas was used as the carrier gas in this experiment meanwhile oxygen gas as the oxidant. The purity of both gases is 99.9% and manufactured by Air Product Sdn. Bhd.

3.3 Preparation of Samples

Biomass samples were cleaned by washing to remove undesired compounds. Then, they were chopped into smaller pieces, dried in an oven at 100 °C for 24 h. This process is important to make sure that the moisture content in the samples is reduced. Before the samples were placed in a furnace, they were ground into smaller particle size. The samples were then sieved to ensure the consistency of the size of below 250 µm. The same preparation steps were repeated for OPF and Kempas. Figure 3.2 shows the procedures for the preparation of biomass samples. Figure 3.3 and Figure 3.4 show the EFB and OPF samples for raw, after drying, and after sieve, respectively. Figure 3.5 illustrates the Kempas samples for raw and after sieving.

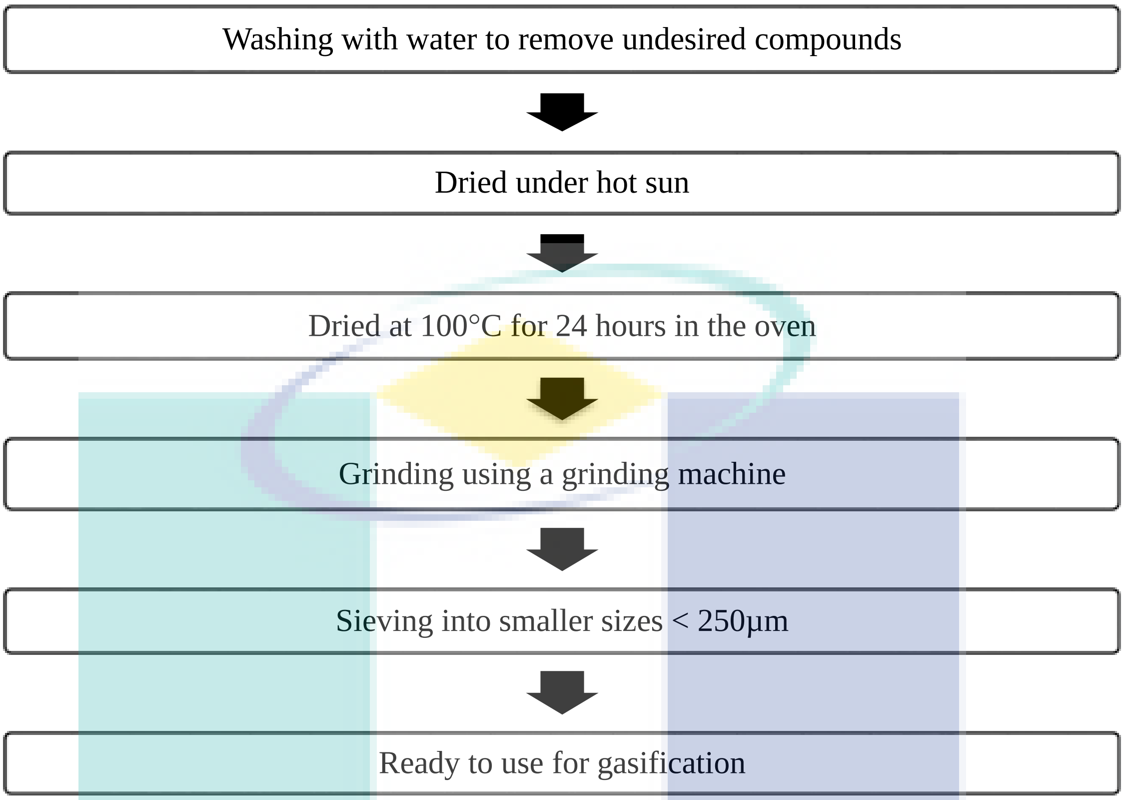
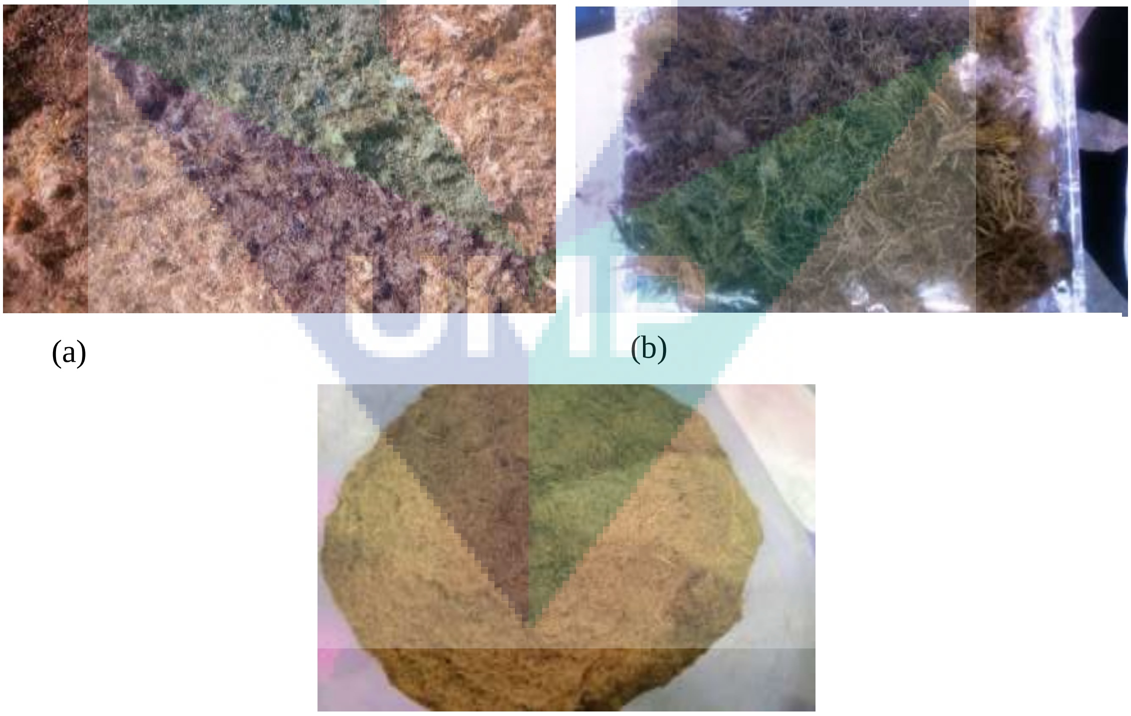


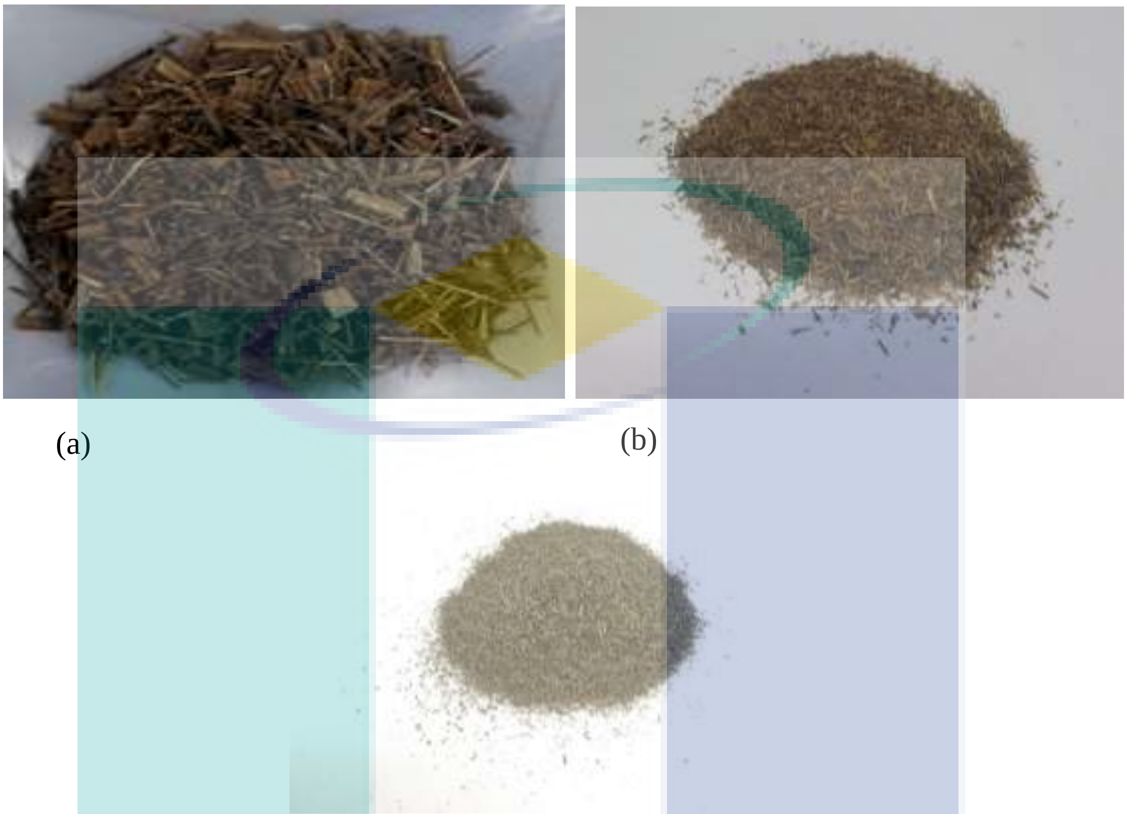
Figure 3.2 Procedures for preparation of biomass samples


(a)

(b)

(c)

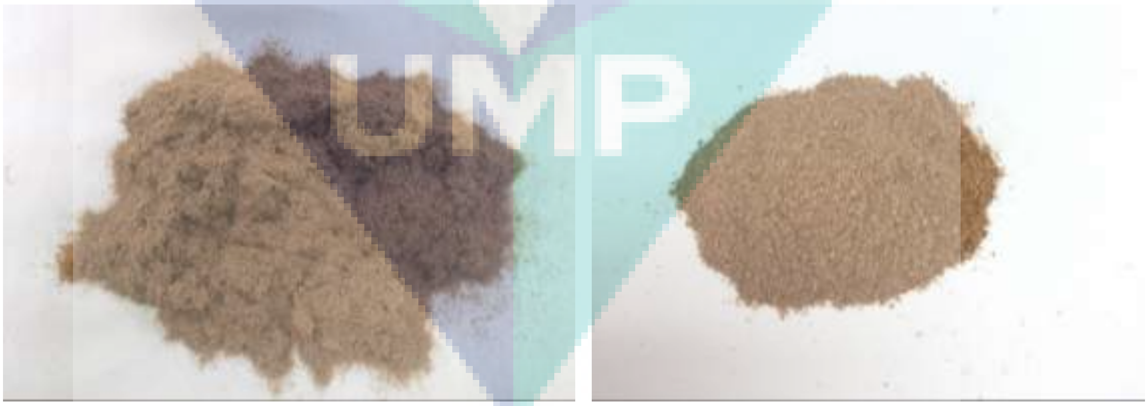
Figure 3.3 (a) Raw EFB, (b) dried EFB, and (c) EFB with size of 250 µm



(a) (b)

(c)

Figure 3.4 (a) Raw OPF, (b) dried OPF, and (c) OPF with size of 250 µm



(a) (b)

Figure 3.5 (a) Raw Kempas and (b) Kempas with size of 250 µm

For coal preparation, it need to be blended to have powder size of coal. After that, the coal and biomass were mixed based on the weight percentage such as B0 (20 g of coal) and B 100 (20 g of biomass). Table 3.1 shows the mixed of coal and biomass for samples preparation.

Table 3.1 Ratio of coal and biomass for samples preparation

Samples	Weight (g)	
	Biomass	Coal
B0	0	20
B10	2	18
B30	6	14
B50	10	10
B100	20	0

3.4 Experimental parameters

In this research, the performance of coal and biomass co-gasification were tested based on a few parameters which were temperature, ER, and biomass ratio. The ER values for this study were determined using Equation 3.1 (Zheng et al,. 2016). The flow rate of O_2 was varied between 2.9 and 4.7 L/min while the flow rate of N_2 was set between 8.8 and 17.6 L/min. Table 3.2 summarizes the experimental conditions performed in this study.

Table 3.2 The experimental conditions

Gasification process	**Temperature (°C)**	**ER**
EFB	700, 750, 800, 850, and 900	0.2, 0.25, 0.3, 0.35, and 0.4
OPF	700, 800, and 900	
Kempas		
Co-Gasification process	**Temperature (°C)**	**Biomass ratio**
Adaro coal and EFB	700, 750, 800, 850, and 900	B0, B10, B30, B50, and B100
Adaro coal and OPF	900	
Adaro coal and Kempas	900	

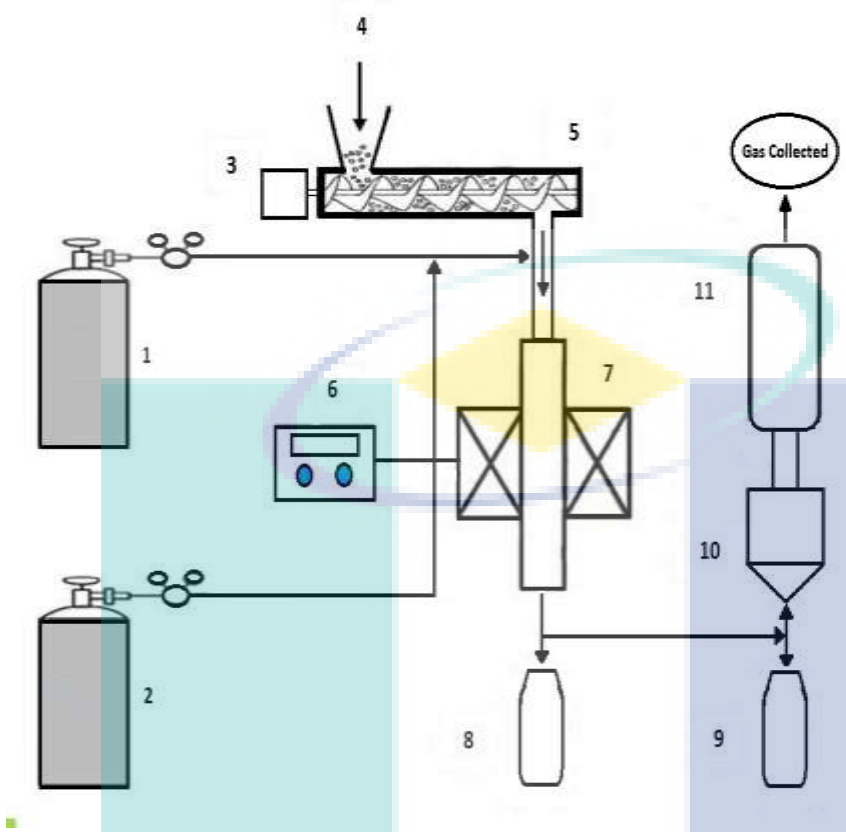
$$ER = \frac{oxygen\ or\ air\ supplied\ (\frac{Nm^3}{h})}{oxygen\ or\ air\ required\ for\ complete\ combustion(\frac{Nm^3}{h})} \qquad 3.1$$

3.5 Experimental Procedures

In the biomass gasification experiments, 20 g of biomass was fed into a gasifier. The temperature was varied between 700 and 900 °C with an increment of 50 °C and ER was varied at 0.2, 0.25, 0.3, 0.35, and 0.4. The gasification process was performed in a laboratory at atmospheric pressure in an entrained flow gasification system.

The samples were put in the reactor on a semi-batch system under the desired air flow rate depending on the ER through manual loading. The value of airflow feed into the gasifier was based on the amount of ER. After reaching the desired temperature, compressed air consisted of N_2 and O_2 was supplied to the gasifier at a constant flow rate. The air supply to the gasifier was mixed, controlled, and monitored by using two flow meters and two valves. The gasifier was heated using temperature controller from 700 to 900 °C at an increment of 50 °C per new run in the furnace using the heating element in the reactor. A screw feeder was used to feed the samples and a motor was used to control the speed of the screw feeder. The furnace is cylindrical with an inside diameter of 4.5 cm and a length of 50 cm and made from stainless steel which can withstand high temperature up to 1100 °C. There are two thermocouples at two different locations, at the bottom and top of the furnace for detecting the inlet and outlet temperatures of the gasifier.

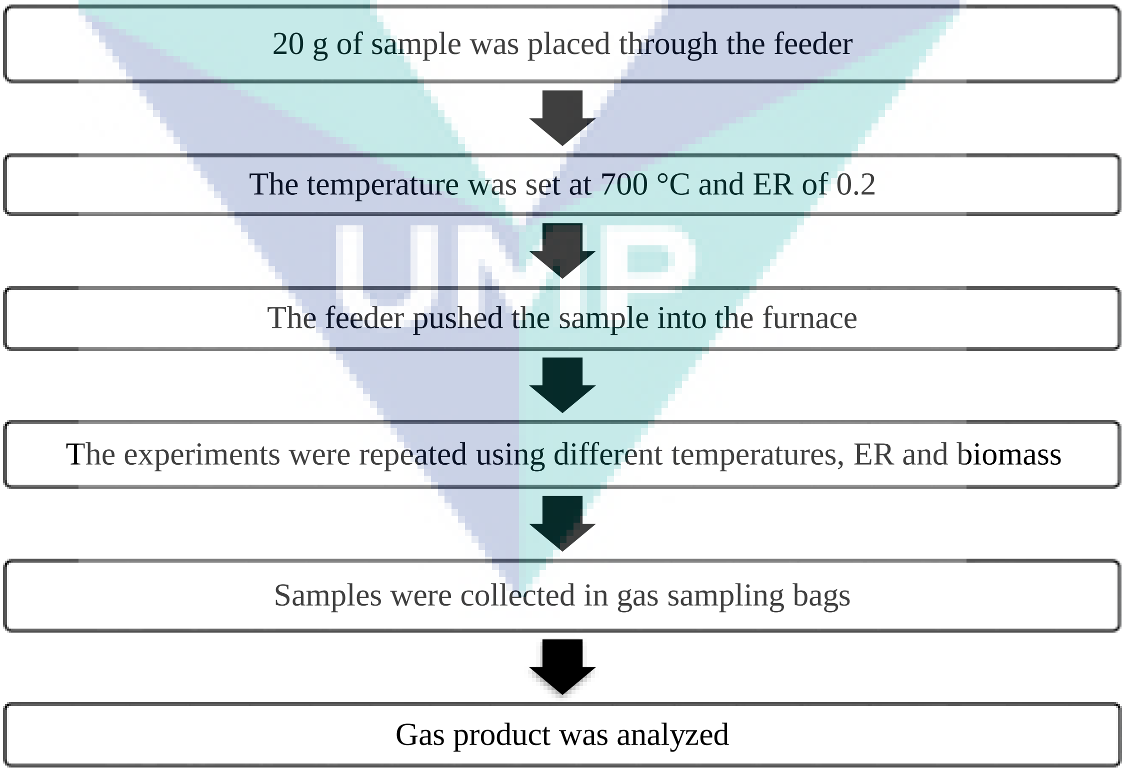
The schematic diagram for the entrained flow gasifier is shown in Figure 3.6. Figure 3.7 is the summary of the experimental procedures. The gasifier was equipped with a cyclone where the dirty outlet gas containing ash, char, tar, and dust particles entered the cyclone separator. The cyclone was used to remove ash and chars from the gas and derived them into the primary and secondary ash collectors which are located at the bottom of the cyclone. The gas was passed through the cyclone to separate the gas and ash produced from the gasification of biomass. Hot gas was then passed through the condenser to reduce the temperature of gas. The gas is collected in the gas sampling bags. The gas was collected in an air tight gas bag with a maximum capacity of 1 L. The gas samples were analyzed using gas chromatography (GC, Agilent Technology, 6890). All experiments were done in triplicates.



Legends

1. Nitrogen gas
2. Oxygen gas
3. Motor
4. Sample feed
5. Screw feeder
6. Temperature controller
7. Reactor
8. Primary ash collector
9. Secondary ash collector
10. Cyclone
11. Condenser

Figure 3.6 Schematic diagram of an entrained flow gasifier



20 g of sample was placed through the feeder

The temperature was set at 700 °C and ER of 0.2

The feeder pushed the sample into the furnace

The experiments were repeated using different temperatures, ER and biomass

Samples were collected in gas sampling bags

Gas product was analyzed

Figure 3.7 The procedure for biomass gasification using an entrained flow gasifier

3.6 Analysis for Biomass Gasification

3.6.1 Ultimate Analysis (UA)

The ultimate analysis (UA) of the solid fuel samples was carried out using a CHNS element analyzer Vario Makro Elemental in Central Lab, UMP. The element analyzer is capable to determine the weight percentage of the elemental carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) (Medic et al., 2012). Thermogravimetric analysis (TGA) was conducted to identify the characteristics of the biomass based on moisture content, volatile matter, fixed carbon, ash, and higher heating value for the biomass and coal. For this experiment, the detailed description on TGA conditions is listed in Table 3.3.

Table 3.3 TGA conditions for biomass and coal analysis

Condition	
Initial Temperature	25 °C
Final Temperature	1000 °C
Heating Rate	10 °C/min
Gas	Nitrogen
Gas flow rate	50 mL/min

3.6.2 Higher Heating Value (HHV) of Biomass

The higher heating value (HHV) is the total energy content released when the fuel is burned in air, including the latent heat contained in the water vapor and thus it is the maximum amount of energy that are potentially recoverable from a given biomass source (McKendry, 2002). HHV can be determined from the results of UA (Medic et al., 2012). Based on Ghassemi & Shahsavan-Markadeh (2013), HHV is determined based on Equation 3.2:

$$HHV\left(\frac{MJ}{kg}\right) = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211A \tag{3.2}$$

where C = mass percentage of carbon in biomass as determined by ultimate analysis

H = mass percentage of hydrogen in biomass as determined by ultimate analysis

S = mass percentage of sulfur in biomass as determined by ultimate analysis

N = mass percentage of nitrogen in biomass as determined by ultimate analysis

A = mass percentage of ash in biomass as determined by ultimate analysis

O = mass percentage of oxygen determined by difference on dry and ash free basis

3.6.3 Gas Chromatography (GC)

Gas chromatography is an analytical separation technique that was used to analyze volatile substances in the gas phase. The gases that can be determined by the GC includes H_2, N_2, CO, CH_4 and CO_2. GC–thermal conductivity detector (GC–TCD, G1530N) was used to determine the composition of produced syngas as illustrated in Figure 3.8. For each sample, the gas composition can be identified after 20 min. The gas compositions may be determined based on the properties given by the GC such as retention time, area, amount/area, and amount.

Figure 3.8 Gas chromatography–thermal conductivity detector (GC–TCD, G1530N)

3.6.4 Higher Heating Value (HHV) of producer gas

Higher heating value (HHV) of fuel is defined as the quantity of heat release by combustion of a specific amount of fuel under normal conditions (McKendry, 2002). Using the standard state of pressure and temperature at 101.3 kPa and 273 K to estimate the HHV of gas composition where the species contents are given in mol%, and their heats of combustion are in MJ/m^3. Equation 3.3 is the formula used to calculate the HHV value (Waldheim & Nilsson, 2001):

$$HHV = \frac{(12.75\, X_{H_2} + 12.63\, X_{CO} + 39.82\, X_{CH_4})}{100} \qquad 3.3$$

where X is the mol% of H_2, CO, and CH_4.

3.6.5 Cold Gas Efficiency (CGE)

One of a measures of a gasification performance is cold gas efficiency (CGE). It is based on the heating values of the initial solid fuel that is converted into product gas. The formula used in this study to calculate CGE is shown in Equation 3.4 (Ishii et al., 2005):

$$CGE = \frac{HHV\ of\ product\ gas}{HHV\ of\ fuel} \times 100 \qquad 3.4$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Composition of Biomass and Coal

Preliminary analysis for the samples used in this study is required to determine the composition of the samples. Ultimate analysis (UA) was one of the analyses used to determine the elemental composition (C, H, N, S, and O) of the samples. In addition, proximate analysis (PA) was conducted to identify the moisture content (MC), fixed carbon (FC), volatile matter (VM), ash, and HHV for the biomass and coal. Table 4.1 shows the UA and PA for biomass and Adaro coal. The PA of biomass and coal were compared with previous studies. Kempas and Adaro coal of this work had higher HHV compared to previous studies. The non-combustible component of wood is water, which makes up to 50% of freshly cut wood. Therefore, the ash content is low (Couto et al., 2013). However, EFB in this work had lower HHV than the previous studies. The FC value for Adaro coal was the highest (38.62%) while OPF was the lowest (0.24%). In addition, the VM from previous studies (Parshetti et al., 2013) was the highest compared to others. Moreover, the MC for OPF was the highest (13.28%) due to the condition of the raw OPF, which was moist and juicy.

Kempas had the highest C content compared to EFB and OPF. Conversely, for the H, N, and S content, EFB was the highest. Meanwhile, OPF had the highest O content. The UA was also performed for the mixture of the three biomasses with the Adaro coal at B50 (50% biomass, 50% coal). When the biomass was mixed with the coal, the UA showed an enhancement in carbon content compared to using biomass alone. Kempas mixture with coal had the highest C, H, and S content. Meanwhile, the highest N and O contents were recorded by the EFB mixture with coal and OPF mixture with coal, respectively.

Table 4.1 Characterization for biomass and coal

PA	MC	FC	VM	Ash	HHV (MJ/kg)	References
EFB	5.977	5.893	68.94	19.19	18.546	This work
OPF	13.28	0.24	79.22	7.260	17.38	
Kempas	7.56	12.30	78.97	1.17	19.76	
Adaro coal	8.54	38.62	39.69	13.15	26.30	
Wood	9.04	13.65	76.70	0.61	16.44	Qin et al. (2012)
Coal	4.18	49.88	30.56	15.38	25.44	Wu et al. (2017)
EFB	4.20	10.41	82.21	3.0	19.45	Parshetti et al. (2013)
UA (wt%)	**Carbon**	**Hydrogen**	**Nitrogen**	**Sulfur**	**Oxygen**	
Adaro coal	63.35	5.810	1.205	0.250	29.390	This work
EFB	43.518	7.255	3.041	0.290	45.896	
OPF	42.875	6.508	2.437	0.275	47.905	
Kempas	47.260	6.674	1.754	0.126	44.186	
EFB + Adaro coal	52.413	5.991	6.722	0.174	34.700	
OPF + Adaro coal	51.299	6.651	1.189	0.154	40.707	
Kempas + Adaro coal	55.756	6.669	1.272	0.257	36.046	

4.2 Gasification of EFB in an Entrained Flow Gasifier

In this section, the gasification of EFB in an entrained flow gasifier is presented. In particular, the effect of temperature in the range of 700 to 900 °C and ER values between 0.2 to 0.4 were tested to determine the influence on gas composition (H_2, CO, and CO_2), HHV, and CGE. However, composition of other gases such as CH_4 was really low, therefore is negligible in the research.

4.2.1 Syngas Production

Figure 4.1, Figure 4.2 and Figure 4.3 show the volume percentage of H_2, CO, and CO_2 produced for EFB as ER was increased from 0.2 to 0.4. Figure 4.1 shows the volume percentage of H_2 produced as temperature increased from 700–900 °C, across the ER values tested. The increase in H_2 percentage can be explained by the Le Chatelier’s principle, in which higher temperatures cause the reactants in exothermic reactions and favor the products in endothermic reactions. Therefore, the reaction of steam reforming

$(CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2)$ strengthened as the temperature increased, resulting in an increase of H_2 content (Li et al., 2009). Moreover, Turn et al. (1998) reported that higher temperature provides more favorable conditions for thermal cracking and steam reforming, which results in higher H_2 production.

When ER value was increased from 0.2 to 0.4, the volume of air supplied into the gasifier was also increased. This caused the air flow rate to control the degree of combustion which in turn, affected the gasification temperature. Higher air flow rate resulted in higher temperature which led to higher biomass conversion and higher quality of fuel (Kumar et al., 2009). However, when ER was high, the degree of combustion also became higher and improved the burning of char to produce CO_2 instead of combustible gases such as H_2 and CO. Thus, this phenomenon caused the production of H_2 to decrease due to the increase of ER (Zheng et al., 2016). Most researchers agreed that there is an optimum ER for gasification reaction in the range of 0.2 to 0.4. Lv et al. (2004) stated that the optimum ER for their work was at 0.23; after 0.23, the H_2 content decreased. Dillibabu and Natarajan (2014) stated that the optimum ER for their work was 0.3. However, Ghassemi and Shahsavan-Markadeh (2013) claimed that when ER increases, H_2 gas composition decreases. It is due to further occurring of hydrogen oxidation, due to presence of more oxygen in system.

The volume percentages for CO and CO_2 for different temperatures and ER are shown in Figure 4.2 and Figure 4.3, respectively. The CO content decreased with increasing temperature, however, the CO_2 content increased. Besides that, the WGS reaction also caused the CO content to decrease as the temperature was increased, so, as the temperature became higher, the CO content decreased (Mohammed et al., 2011). As the ER was increased, the CO content also increased then decreased; meanwhile, CO_2 content increased with the ER. When ER value was increased, the volume of air supplied into the gasifier was also increased, which caused the decrease in H_2 and CO content. Mohammed et al. (2011) and Abdoulmoumine et al. (2014) found that when the ER was increased, the concentration of CO_2 increased due to complete oxidation. This is because when more oxygen is supplied, large amounts of H_2 and CO are oxidized into H_2O and CO_2. This phenomenon also causes CO_2 to increase and H_2 and CO to decrease as ER is increased (Zheng et al., 2016).

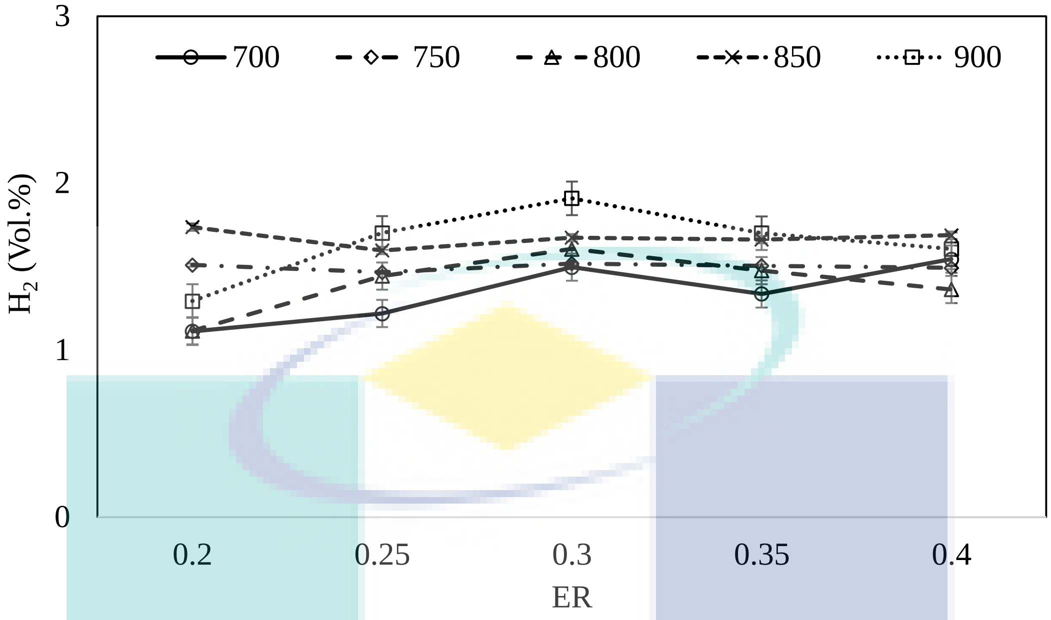


Figure 4.1 H_2 production versus ER

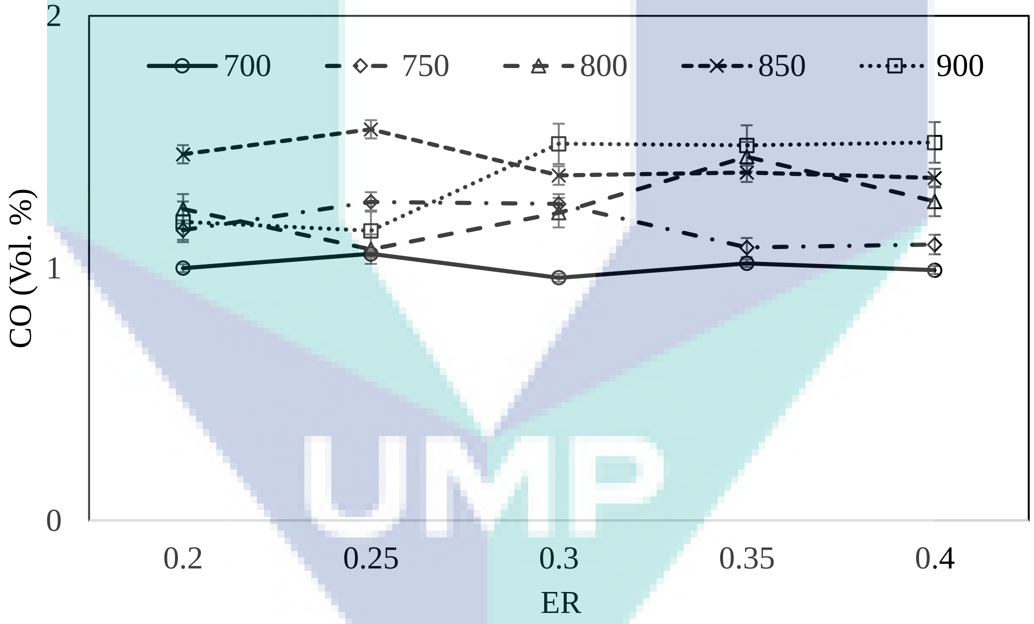


Figure 4.2 CO production versus ER

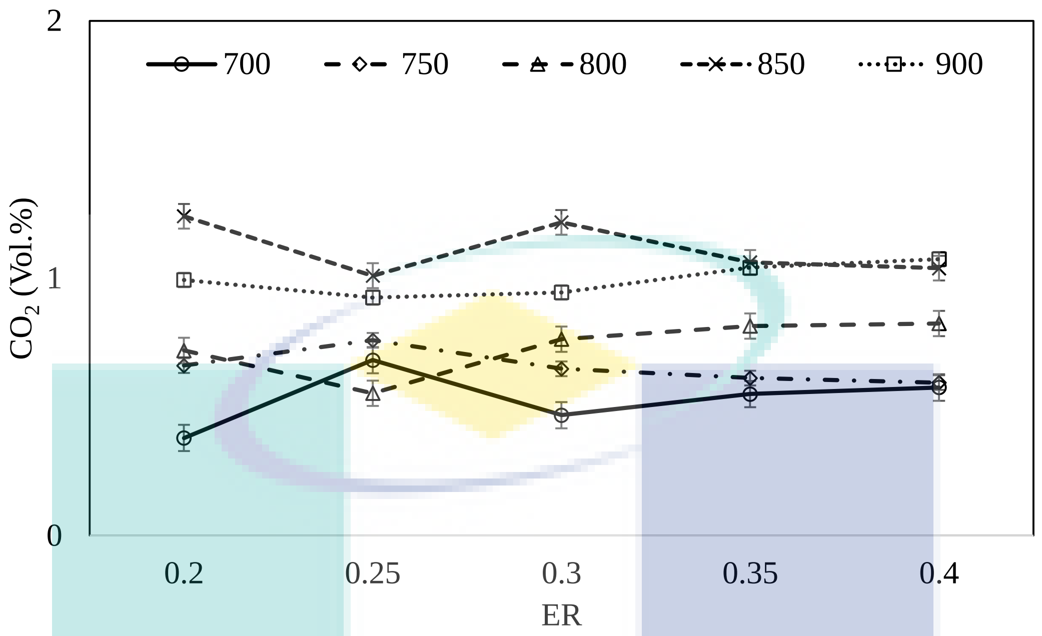


Figure 4.3 CO_2 production versus ER

4.2.2 The Effect of Operating Temperature and ER on HHV and CGE

The effects of temperature and ER on HHV production are shown in Figure 4.4 and Figure 4.5. Based on the experiment, HHV of product gas increased with temperature. The greater increase in HHV from 700 to 900 °C was possibly due to the entrained flow gasifier that was used in this work and the presence of hydrocarbons in the product gas. Higher temperature causes gas yield and carbon conversion to increase, thus resulting in the increase in the HHV of the gas. The HHV of the gas increases with temperature because of the rise in H_2 content in the gas mixture as it has a greater calorific value (Dillibabu & Natarajan, 2014). In this work, the H_2 and CO produced were increased from 700 to 900 °C, therefore resulting in a higher increase in HHV value.

Some researchers claimed that when temperature increases, HHV of gas increases but the increment is almost constant (Ghassemi & Shahsavan-Markadeh, 2013), which suggests that temperatures higher than 700 °C have no impact on HHV. There are also researchers who claim that HHV of gas decreases with temperature due to the decrease in the amount of hydrocarbon (Lv et al., 2004). The HHV formula used in this work is based on Waldheim and Nilsson (2001) (Equation 3.3). The HHV formula for Ghassemi and Shahsavan-Markadeh (2013) is not given while the HHV formula for Dillibabu and Natarajan (2014) is different that of from Lv et al. (2004) and no further discussion was offered. So this might be the reason the HHV values are different from researchers and this work.

From the experiment, the HHV of product gas increased then decreased as ER was increased. This is because although ER promoted gasification reactions, when ER continued to increase, there was a reduction in H_2 and CO gas while H_2 and CO possess high calorific value (Ghassemi & Shahsavan-Markadeh, 2013; Thanapal et al., 2011). When ER increases, oxidation reactions and combustion are enhanced, causing H_2 and CO content to decrease and CO_2 content to increase. Hence, the heating value of product gas also decreases. In addition, the decrease in HHV is also caused by the decrease in methane and other light hydrocarbon concentration as the ER increases (Mansaray et al., 1999). Besides, at higher ER, the concentration of N_2 is higher which effected with diluting effect on the product gas, thus causing the energy content to be lower (Mansaray et al., 1999).

Thus, from the research, the optimum ER was 0.3 where the production of HHV recorded at higher. Other researchers also reported the similar range trend with their results. Alauddin et al. (2010) selected 0.23 as the optimum ER for their work. Dillibabu and Natarajan (2014) stated that the optimum ER to achieve the maximum calorific value of the product gas was 0.3. Figure 4.5 shows that when ER increases more than 0.3, the HHV of product gas decreases (Ghassemi & Shahsavan-Markadeh, 2013).

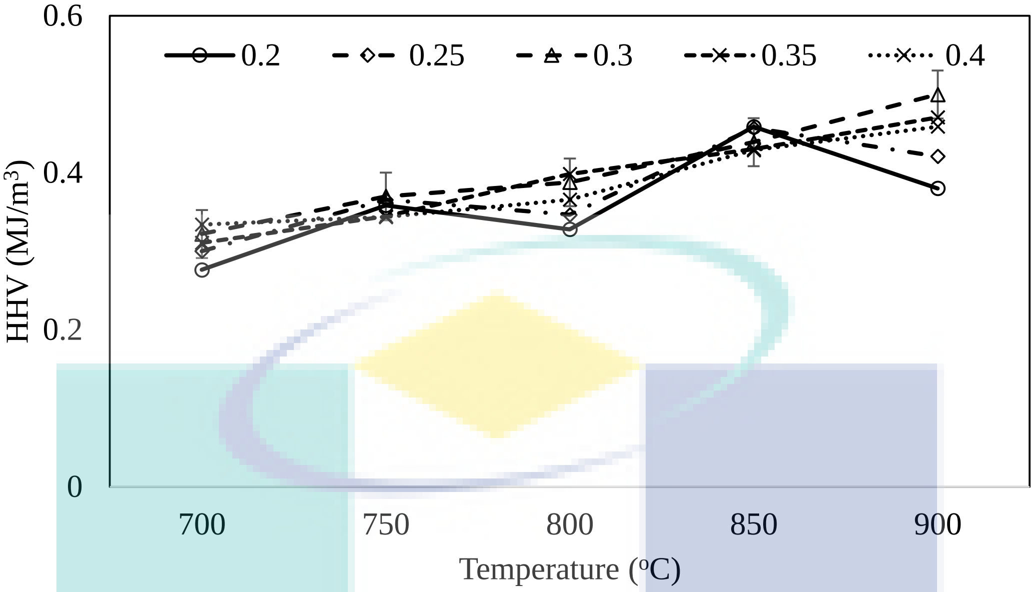


Figure 4.4 HHV at different temperatures

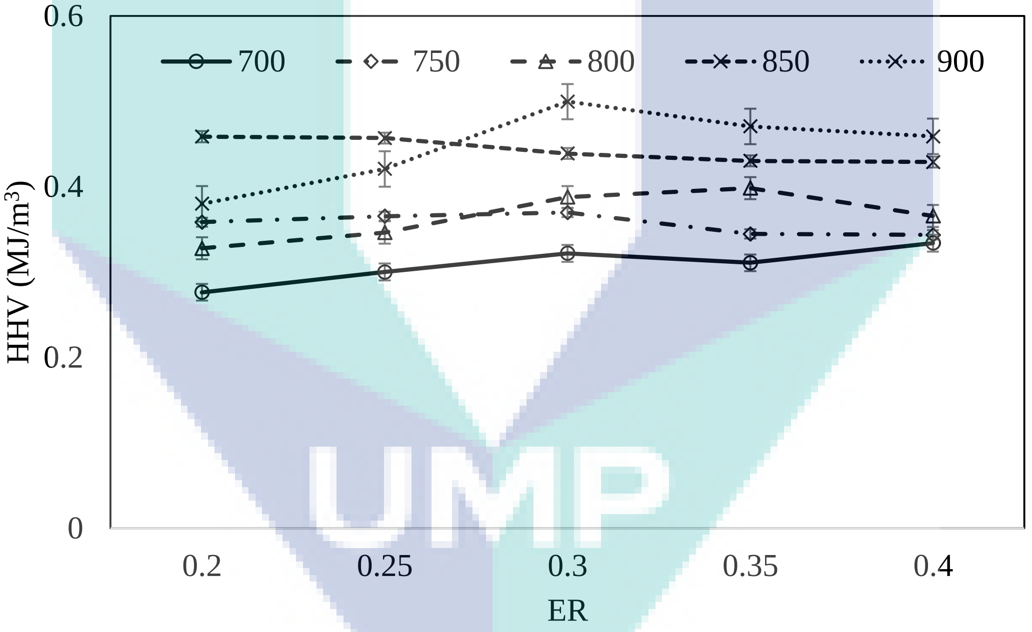


Figure 4.5 HHV at different ER ratios

Figure 4.6 shows the CGE versus different temperatures from 700 to 900 °C with variations of ER. As the temperature increases, the CGE value also increases. This is due to promotion of the combustion of char by the oxidation ($C + O_2 \leftrightarrow CO_2$) and partial oxidation ($2C + O_2 \leftrightarrow 2CO$) reaction, which promote the pyrolysis reaction of biomass and the gasification reactions of Boudouard (Equation 2.6) and water gas (Equation 2.5) reaction (Wang et al., 2007).

Figure 4.7 shows the CGE value at different ER. The most optimum CGE was at ER = 0.3, after which it decreased with increasing ER. When ER is increased, the energy conversion is higher, which also means higher CGE values. However, as ER was further increased, the CGE decreased. When ER was increased from 0.2 to 0.3, it increased the gasification temperature and provided a favorable condition for the production of H_2 and CO, thus increasing gas yield. Both H_2 and CO gases have high heating value. However, too high ER caused complete oxidation and produced CO_2 instead of producing valuable gases H_2 and CO (Ghassemi and Shahsavan-Markadeh, 2013). Thus, CGE decreased in later stage, when ER was more than 0.3. This can be attributed to the fact that when solid biomass is used in gasification, there is always unburned carbon in fly ash which causes the decrease of CGE (Zheng et al., 2016). A similar finding was also reported by Cao et al. (2006), who concluded that from the total chemical energy of biomass, 15%–20% of the chemical energy loss was due to the unburned carbon of fly ash. It is considered that the increase of the supplied air into the gasifier led to the further combustion of the gas and dilution of the gas by the addition of nitrogen in the air, which resulted in the decrease of the HHV of the gas and the cold gas efficiency (Wang et al., 2007).

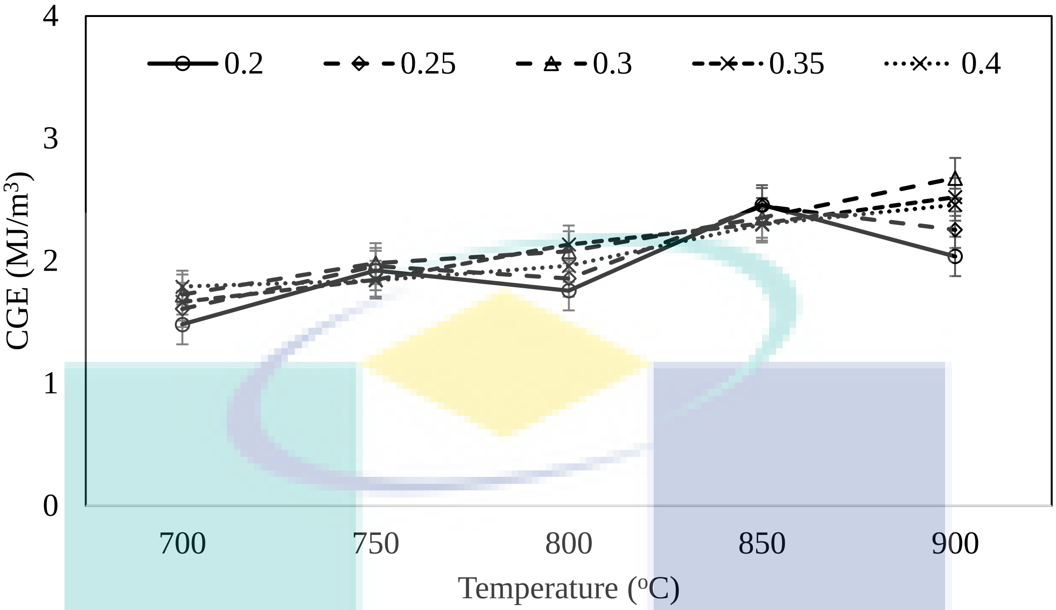


Figure 4.6 CGE at different temperatures

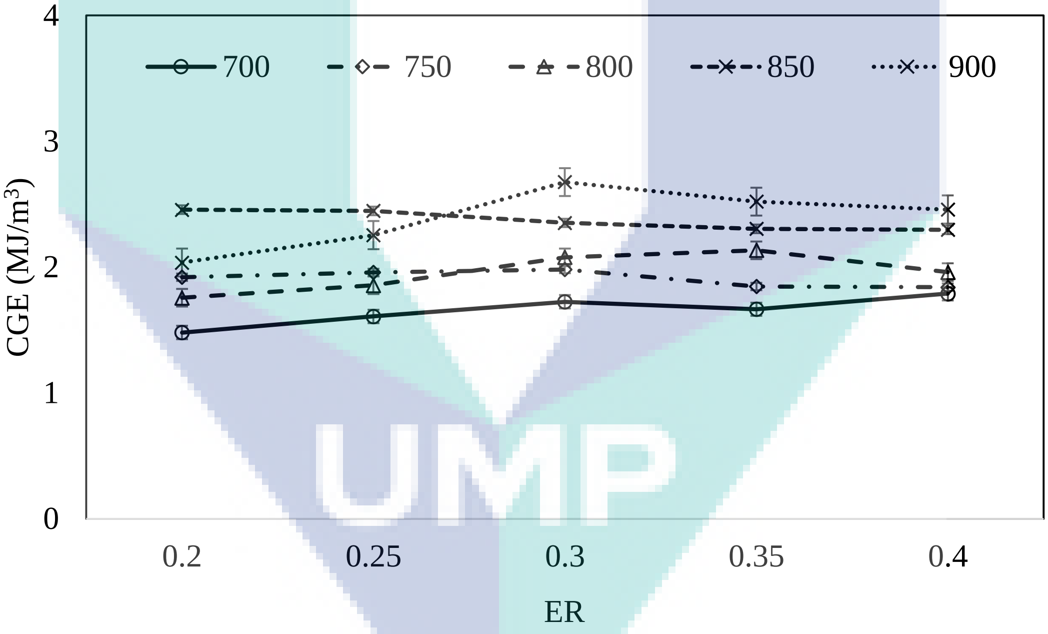


Figure 4.7 CGE at different ER ratios

4.3 The Co-Gasification of EFB and Adaro Coal

The effects of temperature in the range of 700 to 900 °C and mass ratio from B0 to B100 on syngas composition, HHV, and CGE were determined.

4.3.1 Co-Gasification of EFB and Adaro Coal for Syngas Production

The effect on volume percentage of syngas can be seen when the mass ratio of biomass/coal was increased with increasing of temperature. Figure 4.8 shows the effect of biomass ratio on production of H_2 at different temperatures. The H_2 produced initially increased, but then slightly decreased when the temperature reached 800 °C. As the temperature increases, the endothermic reactions for Boudouard, water gas, and steam reforming are promoted, thus increasing the H_2 content (Wu et al., 2017). For the co-gasification reaction, the coal and biomass mixture contains higher volatile matter and less moisture compared to pure coal, hence producing less H_2 (Li et al., 2010; Velez et al., 2009).

Figure 4.9 and Figure 4.10 show the analyses for the effect of different temperatures at various biomass ratios on CO and CO_2 production, respectively. The production of CO_2 slightly decreased while CO production increased throughout the experiments at various conditions. As the biomass ratio increases, this influences the melting of biomass ash and blocking pore of pyrolysis char that occurs which affects the gasification reaction. With increasing biomass ratio, the ratio of hydrogen and carbon in raw materials increases, which influences the formation of H_2 and CO (Wu et al., 2017). The decrease in CO_2 production can be explained by the consumption of CO_2 by the dry reforming reaction of CH_4 ($CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$) (Andre et al., 2005), which causes the increase in CO production as the temperature increases. Furthermore, the WGS reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) and the Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$) are believed to be the most influential reactions to increase the CO production while reducing the formation of CO_2. This is consistent with the study by other researchers (Velez et al., 2009).

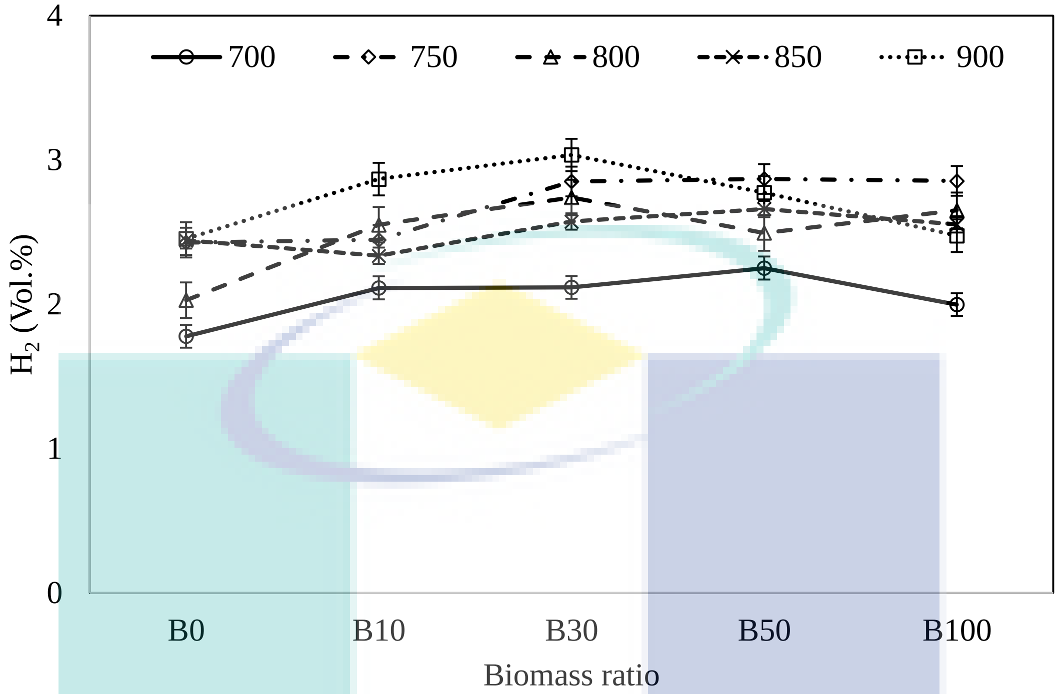


Figure 4.8 H_2 production versus biomass ratio

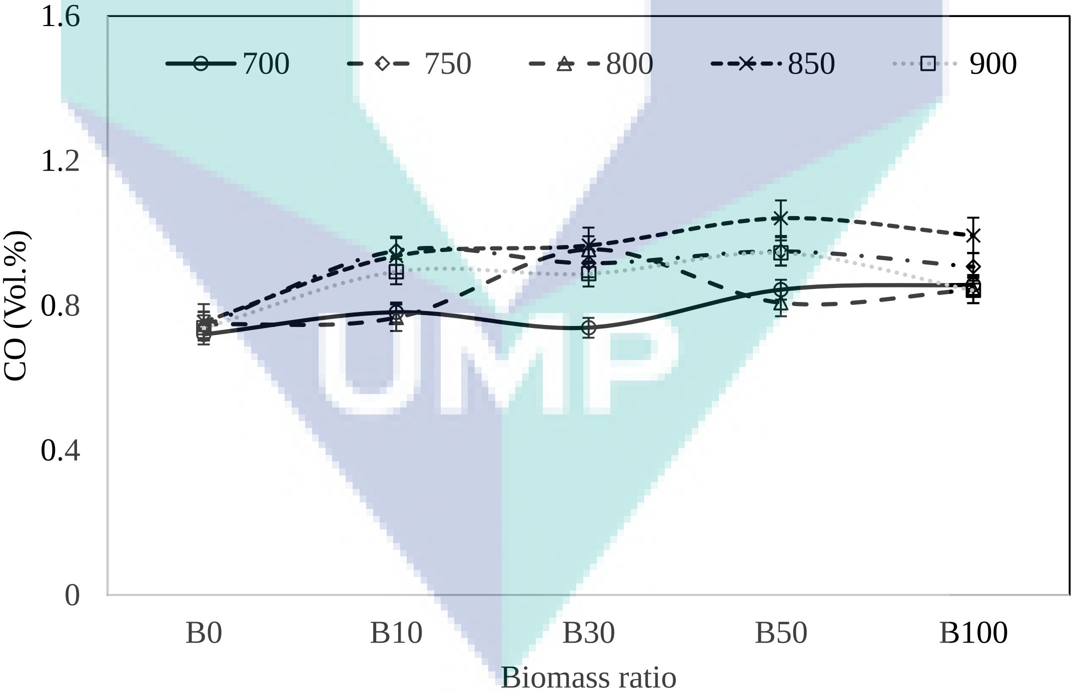


Figure 4.9 CO production versus biomass ratio

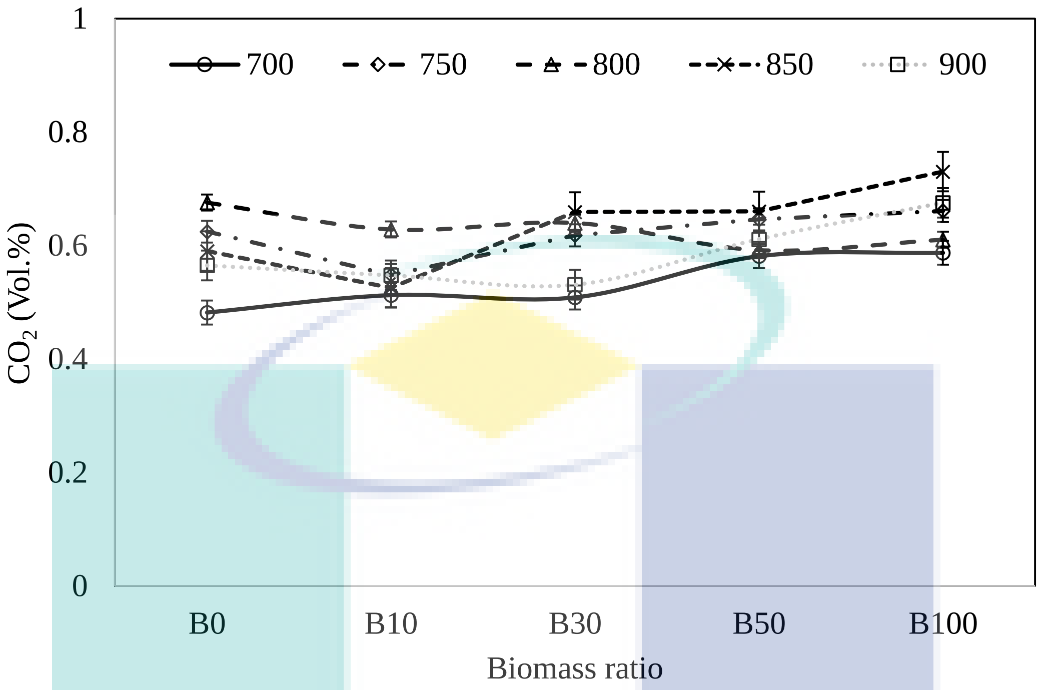


Figure 4.10 CO_2 production versus biomass ratio

4.3.2 The HHV and CGE

Figure 4.11 and Figure 4.12 show the HHV value for the co-gasification at difference mass ratios for various temperatures. With the rise in temperature and mass ratio, the HHV increased because of the increase in H_2 content (Hernandez et al., 2010). However, as the mass ratio increased from B30 to B100, the HHV slightly decreased. According to Andre et al. (2005), this phenomenon may be caused by the reduction production of methane and hydrocarbon, due to the reduced amount of fixed carbon in coal (increased biomass).

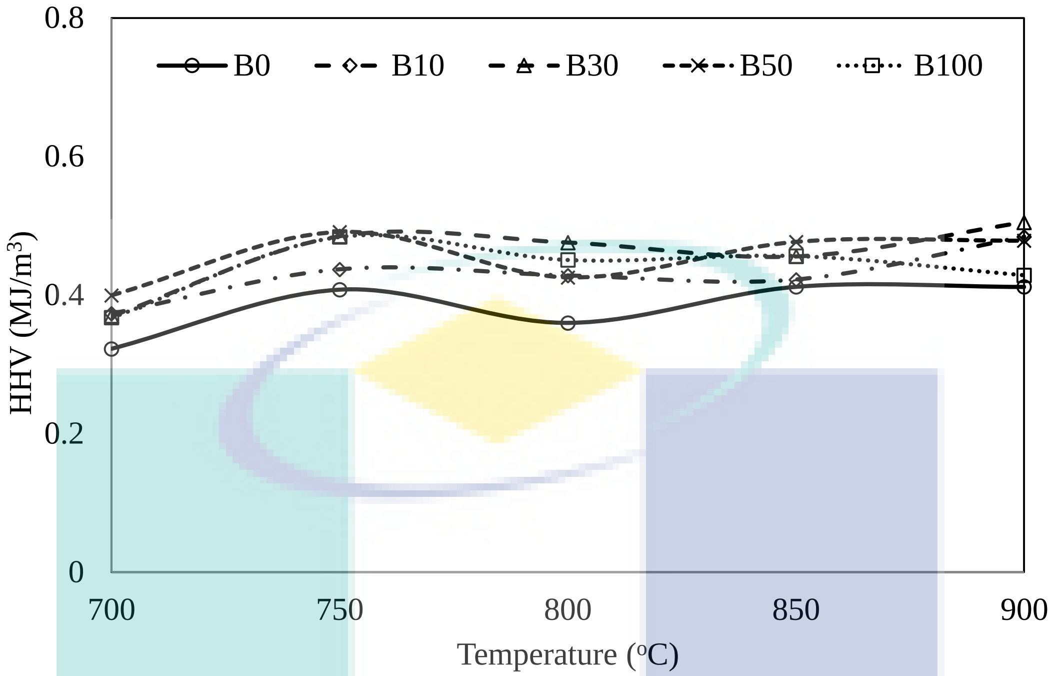


Figure 4.11	HHV at different temperatures

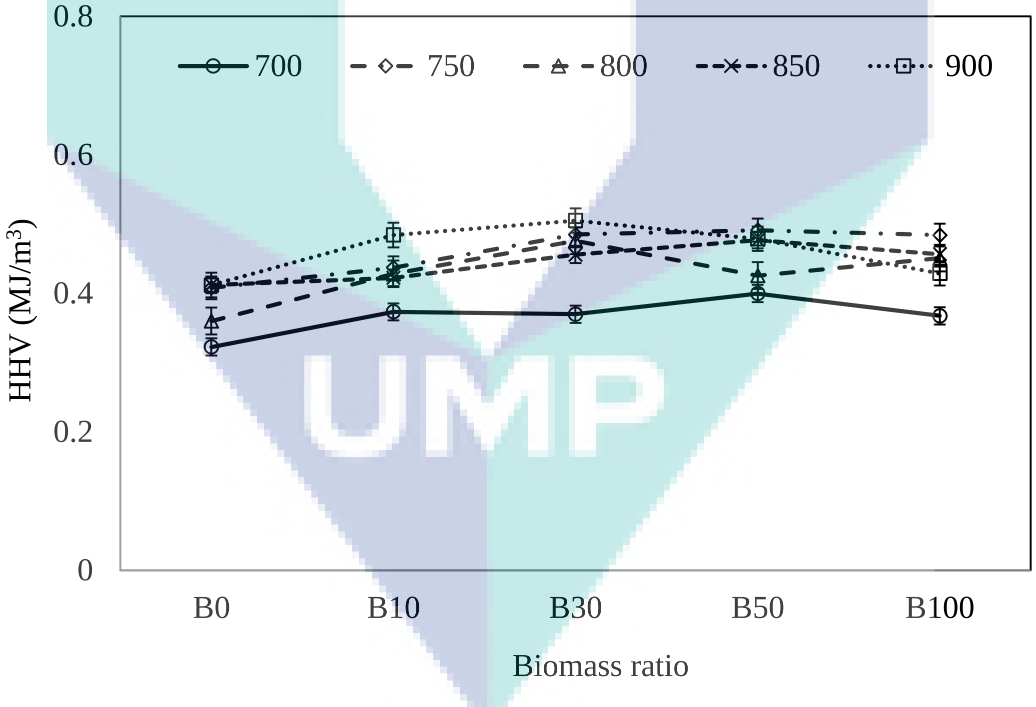


Figure 4.12	HHV at different biomass ratios

The effect on CGE value for co-gasification at various mass ratios and temperatures is illustrated in Figure 4.13 and Figure 4.14. The CGE is defined as the ratio of the HHV of the produced syngas over the HHV of the original fuel in percentage by

Ishii et al. (2005). The CGE shows a positive trend when the operating temperature was increased from 700 to 900 °C as well as when the mass ratio of biomass to coal was increased. This is due to the increase in the production of the syngas, H_2, and CO (Hernandez et al., 2010). A synergistic effect was also observed at B30, where at this point, the HHV and CGE were at their highest values. A similar observation was made by Ding et al. (2014), who determined the strongest synergistic effect at a blending ratio of 50%.

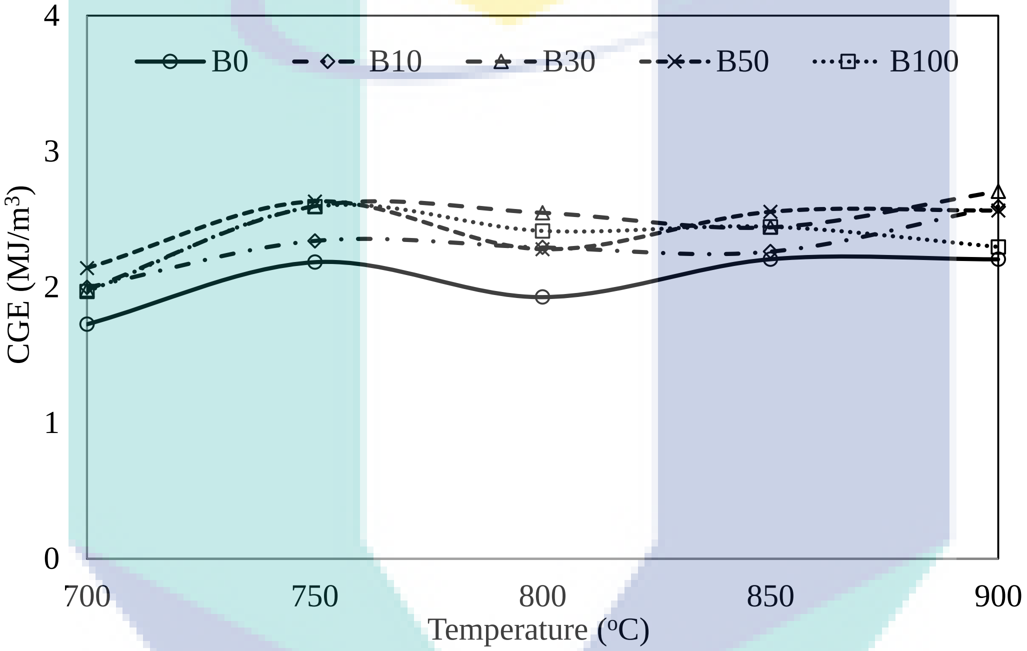


Figure 4.13 CGE at different temperatures

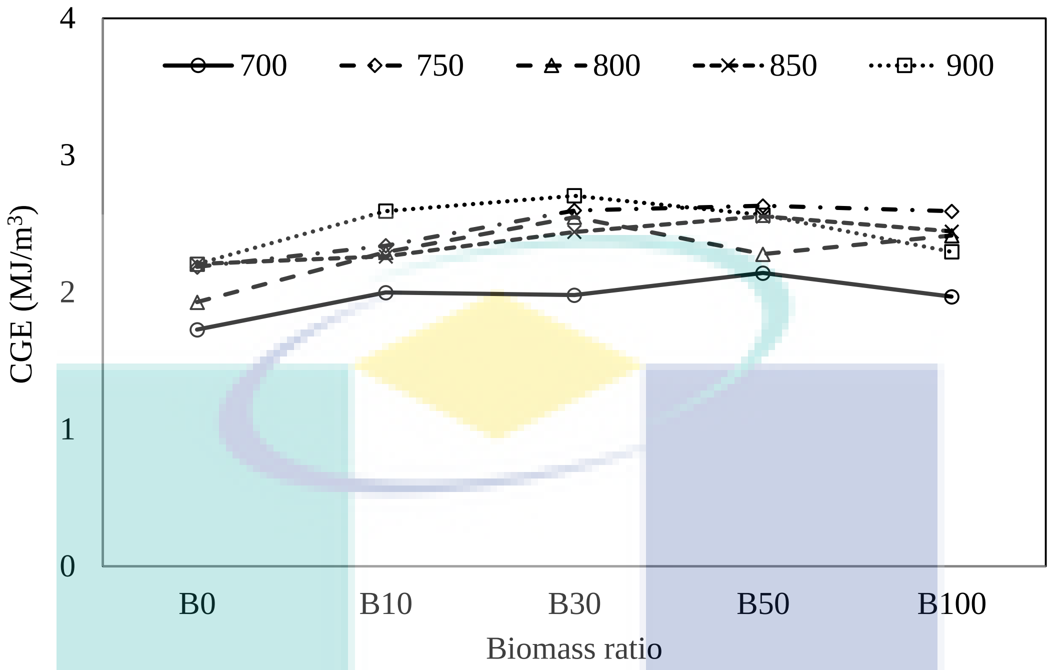


Figure 4.14 CGE at different biomass ratios

4.4 Comparison of Kempas and OPF Gasification

The results and discussions for biomass gasification of Kempas and OPF in an entrained flow gasifier are presented in this section. OPF was selected as it is also considered as one of the abundant palm oil wastes besides EFB. Thus, OPF and Kempas were chosen as feedstock to explore the potential of these two biomasses to be used for the gasification process. Three temperatures of 700, 800, and 900 °C, as well as ER values between 0.2 to 0.4, were tested to determine their influence on syngas composition, HHV, and CGE.

4.4.1 Production of H_2, CO, and CO_2

From Figure 4.15, the H_2 production for Kempas showed an increment with ER from 0.2 to 0.3 but decreased when ER was higher than 0.35. Similarly, H_2 content for OPF increased initially but then decreased when ER was higher than 0.3. This trend agrees fairly well with other researchers, who reported that when the ER increases, H_2 gas composition decreases (Qin et al., 2012). Decreasing of H_2 is most probably due to the excess air ratio when O_2 is supplied to the system, thus generating H_2O instead of H_2. On the other hand, as the temperature increases, H_2 concentration increases as well.

According to the Le Chatelier's principle, higher temperatures favor the reactants in the exothermic reactions and the products in the endothermic reactions (Atnaw et al., 2013). This also suggests that the Boudouard, steam reforming, and the water gas reactions are the dominating reactions at higher reaction temperatures. Thus, the increase in temperature strengthens the endothermic reactions, resulting in the increase of H_2 concentrations (Salleh et al., 2010). Moreover, at higher temperature, further reactions such as tar cracking and shift reaction could occur, which may lead to the production of incondensable gases such as H_2 (Mohammed et al., 2011).

The CO productions for OPF and Kempas are shown in Figure 4.16. The concentration of CO showed a slight increment as ER was increased up to 0.35, but then decreased at higher ER. This suggests that the complete oxidation process ($C + O_2 \leftrightarrow CO_2$) takes place as ER is increased due to excess air. This is consistent with the findings of other researchers (Zhou et al., 2009). As the operating temperature was increased to 800 °C, the CO content decreased, though further increase in the temperature caused it to increase. This could be attributed to secondary reactions that is triggered at higher temperatures which may increase CO concentration (Mohammed at el., 2011). The reversible reactions for Boudouard may also play an important role, whereby in line with the Le Chatelier's principle, at higher temperature, the exothermic reaction favors the reactant and endothermic reaction favors the products, which influence the increase in CO concentration (Umeki et al., 2010).

Figure 4.17 shows the CO_2 production for OPF and Kempas gasification. When the ER was increased, CO_2 composition also increased. This is because as ER is increased, greater amount of oxygen is available, which allows for complete combustion and produces CO_2 (Mohammed et al., 2011). Conversely, when the operating temperature was increased from 700 to 800 °C, the concentration of CO_2 decreased but then increased at 900 °C. This trend suggests that CO_2 may be consumed by the dry reforming reaction (Qin et al., 2012).

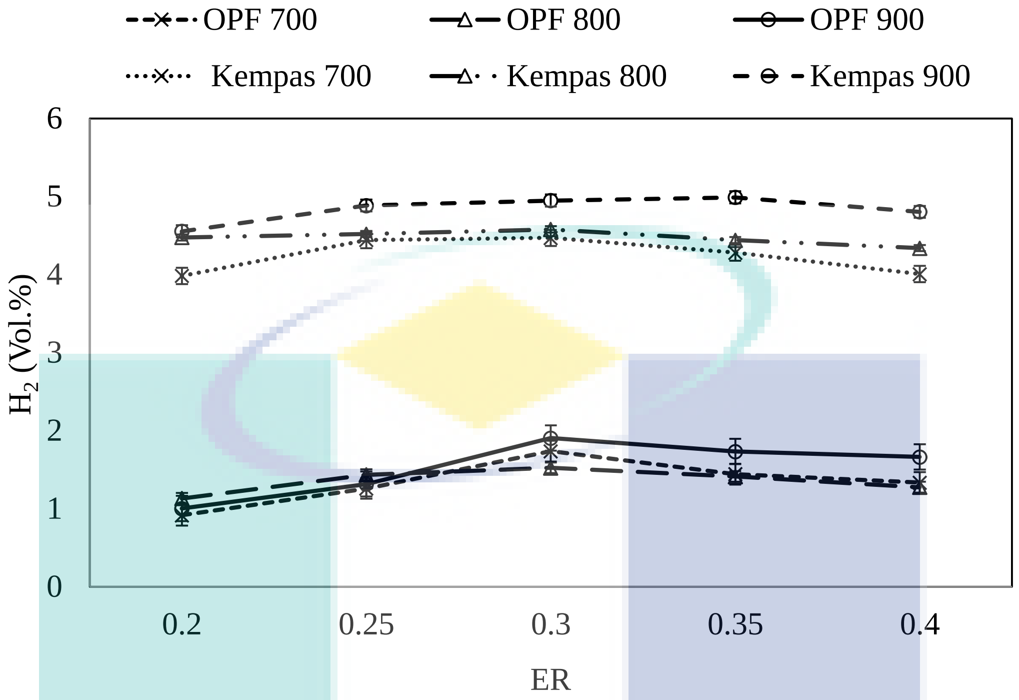


Figure 4.15 H_2 production versus ER

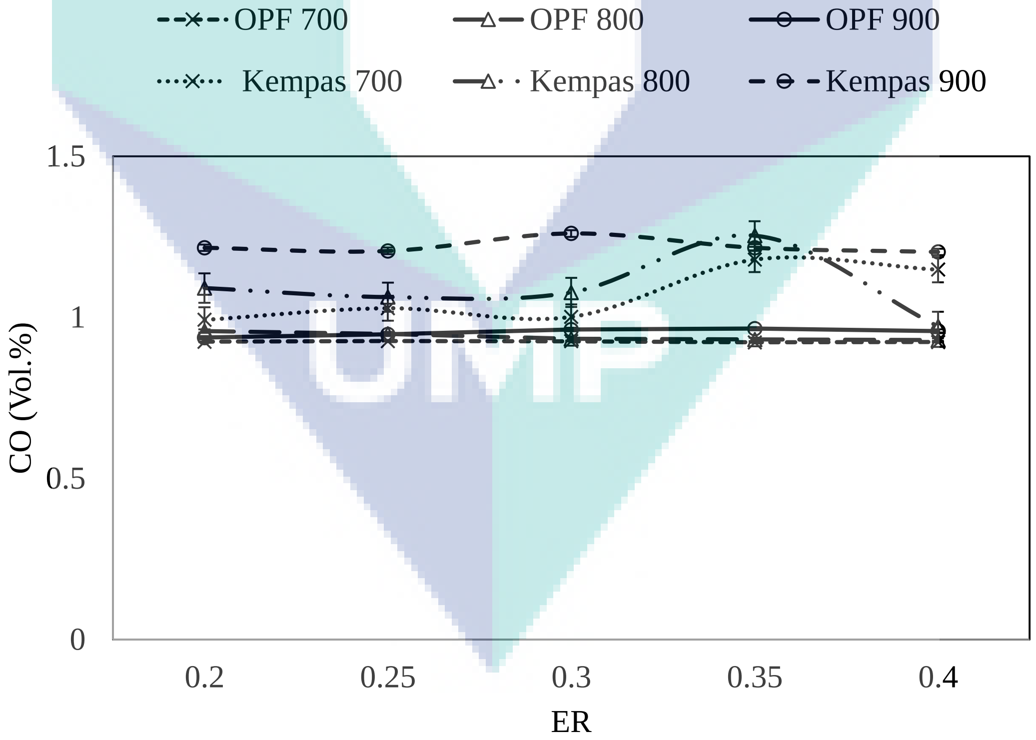


Figure 4.16 CO production versus ER

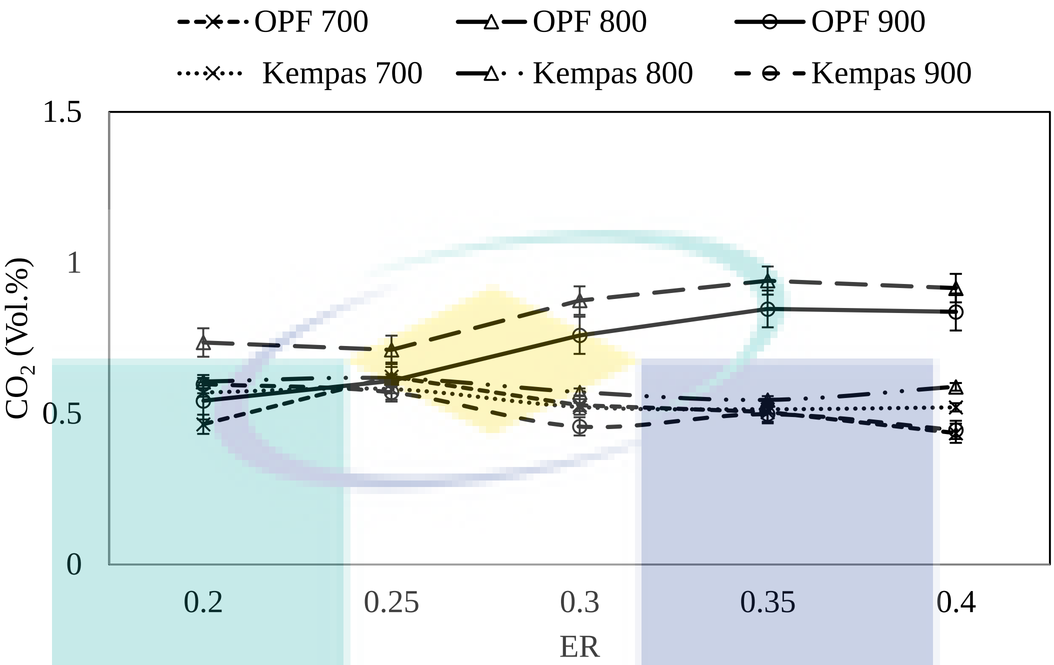


Figure 4.17 CO_2 production versus ER

4.4.2 The Comparison of HHV and CGE for Kempas and OPF Gasification

Figure 4.18 illustrates the HHV for Kempas and OPF at various operating temperatures and ER. The maximum HHV achieved was 0.93 MJ/m^3 for Kempas and 0.41 MJ/m^3 for OPF at ER of 0.35 and 0.3, respectively. A higher HHV for Kempas can be seen because the production of H_2 and CO for Kempas is higher than that of OPF. Similar to the previous compositional trend, the HHV demonstrates an increasing trend from the ER values of 0.2 to 0.35, and subsequently decreased onwards. This is because when more air is supplied to the system, this will lead to complete combustion of syngas and subsequently the dilution of produced gas by N_2 in air occurs, thus resulting in the decrease of HHV (Wang et al., 2007). According to Franco et al. (2003), the decrease of HHV can be caused by the increase in the presence of non-combustible gases as the temperature is increased. The WGS reaction becomes dominant, thus leading to the increase of CO_2 content (Wang et al., 2007).

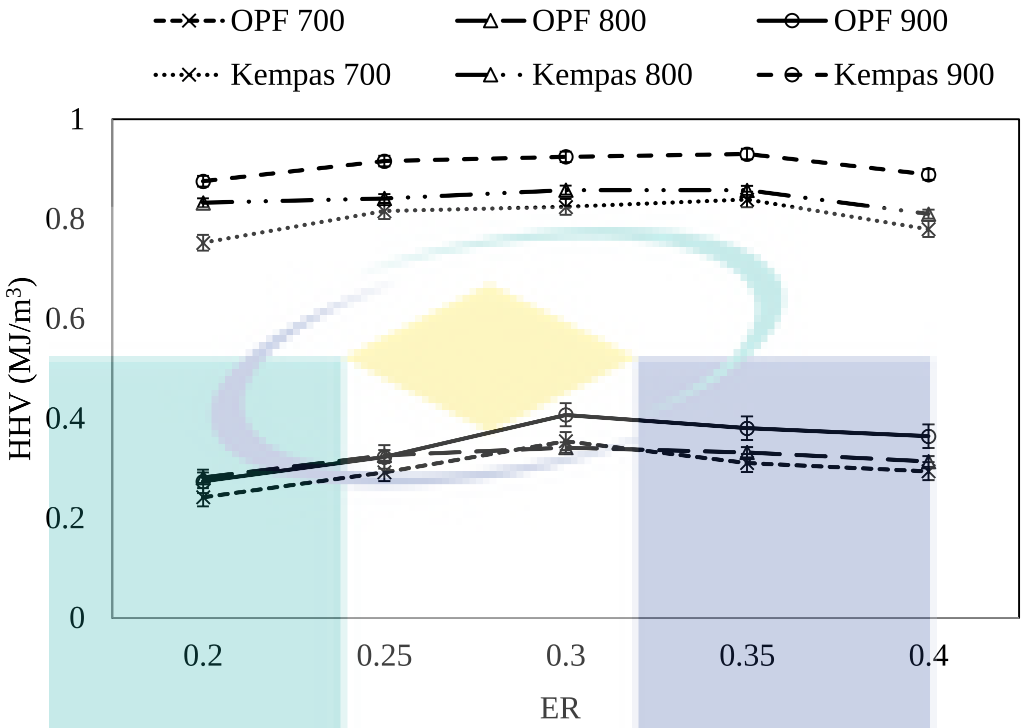


Figure 4.18 HHV at different ER

Another important indicator of gasification performance is the CGE. Figure 4.19 shows that as the temperature increased from 700 to 900 °C, the CGE also increased. Similar to HHV, the increase of ER from 0.2 to 0.35 resulted in higher CGE value. However, as ER was further increased, CGE value decreased. When the ER value was between 0.2 and 0.35, the productions of H_2 and CO were high as well. However, when ER was too high, complete oxidation process occurred, producing CO_2 instead of H_2 and CO, which in turn reduced the CGE values (Ghassemi & Shahsavan-Markadeh, 2014). As the HHV of Kempas can been observed that higher OPF which can be explained by the higher HHV production of Kempas than OPF. The maximum CGE for Kempas was 4.98 MJ/m^3 at ER of 0.35 and 900 °C, while for OPF, the highest CGE was 2.18 MJ/m^3 at ER of 0.3, also at 900 °C.

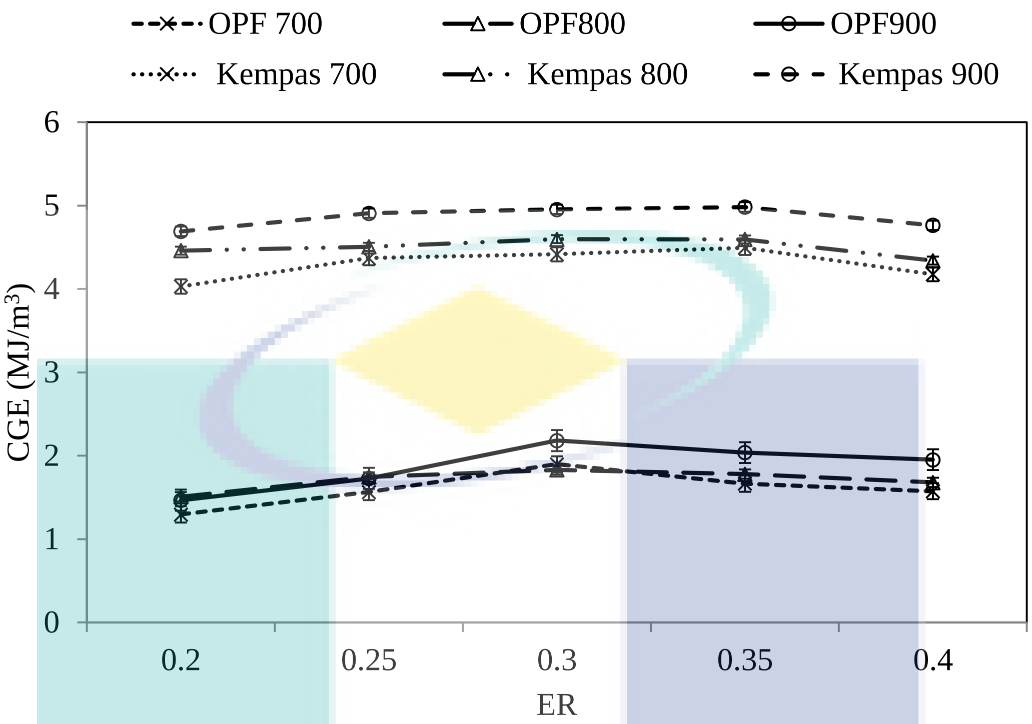


Figure 4.19 CGE at different ER

4.5 Evaluation of Co-Gasification of EFB, OPF, and Kempas with Adaro Coal

The evaluation of co-gasification of EFB, OPF, and Kempas with Adaro coal in an entrained flow gasifier is presented in this section. EFB has been widely used and somewhat proven able to produce relatively high amount of syngas. The utilization of OPF and Kempas for co-gasification process was done to evaluate their potentials in the production of syngas with similar parameters. The effects of biomass ratio between B0 to B100 mixtures at a fixed temperature of 900 °C on syngas composition, HHV, and CGE were determined. The comparison for syngas production on different types of biomass is shown in this section.

4.5.1 Syngas Production for EFB, OPF, and Kempas Co-Gasification

Figure 4.20 illustrates the production of H_2 for the mixture of EFB, OPF, and Kempas with Adaro coal at biomass ratio of B0 to B100. The H_2 volume percentage increased as the biomass ratio increased initially, but then decreased at biomass ratio higher than B30 for both OPF and EFB. Meanwhile for Kempas, the H_2 production showed a slight decrease only when the biomass ratio was above B50. The increase in both the CO and H_2 contents in the syngas suggests that the char gasification reactions are enhanced when gasifying biomass and coal mixtures, probably due to the higher reactivity of the former (Hernandez et al., 2010). The decrease in H_2 production may be influenced by the methanation reaction ($C + 2H_2 \leftrightarrow CH_4$) that converts carbon and hydrogen to form CH_4 (Velez et al., 2009). The production of H_2 for Kempas and coal mixtures was higher than those of OPF and EFB with coal mixtures. This may be caused by the higher percentage of elemental hydrogen in Kempas than in OPF and EFB, where it may increase the H_2 formation (Wu et al., 2017). The CO production at various coal and biomass ratios is shown in Figure 4.21. The synergistic effects were evident at B30, which is consistent with previous studies (Seggiani et al., 2012). The increase in CO production can be caused by partial oxidation reaction (Equation 2.2), where some oxygen from biomass pyrolysis reacts with carbon from coal (Seo et al., 2010).

Figure 4.22 illustrates the production of CO_2, which shows that the volume percentage of CO_2 decreased between B0 and B50, but then increased slightly at biomass ratio above B50. The decreasing of CO_2 production can be explained by the consumption of CO_2 by dry reforming reaction ($CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$) of CH_4 (Franco et al., 2003; Andre et al., 2005). A synergistic effect was noticeable when the blending ratio was between 20% to 50%. This can be due to the initially released CO_2 enhancing the synergistic effects of B50 mixture, followed by H_2 and CO (Hu et al., 2017).

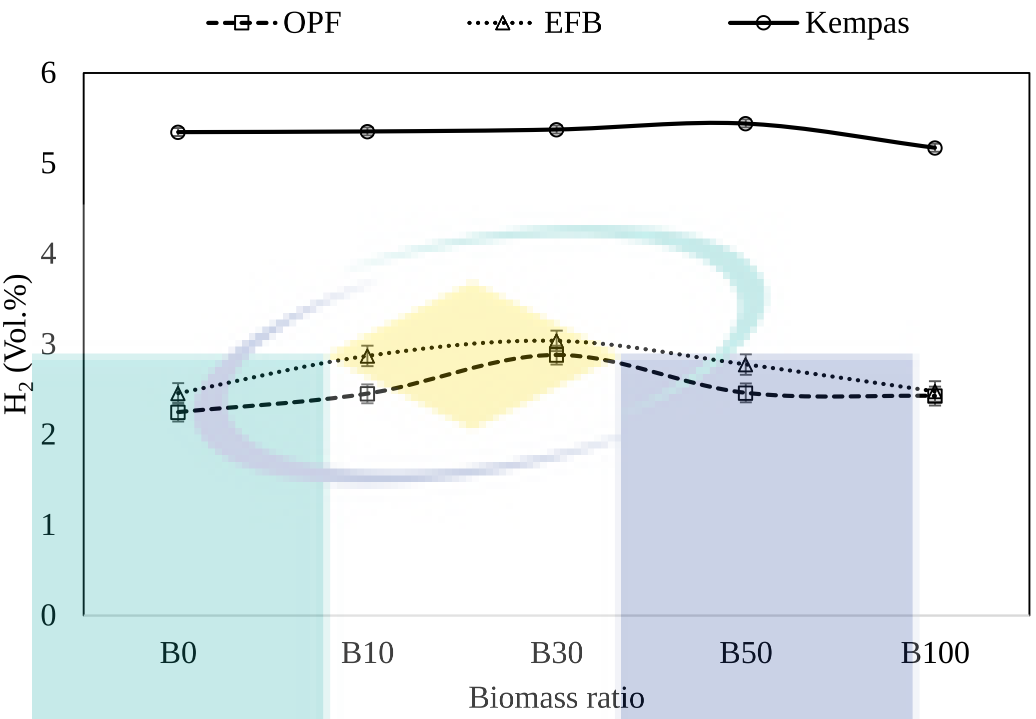


Figure 4.20 H_2 at various biomass ratios

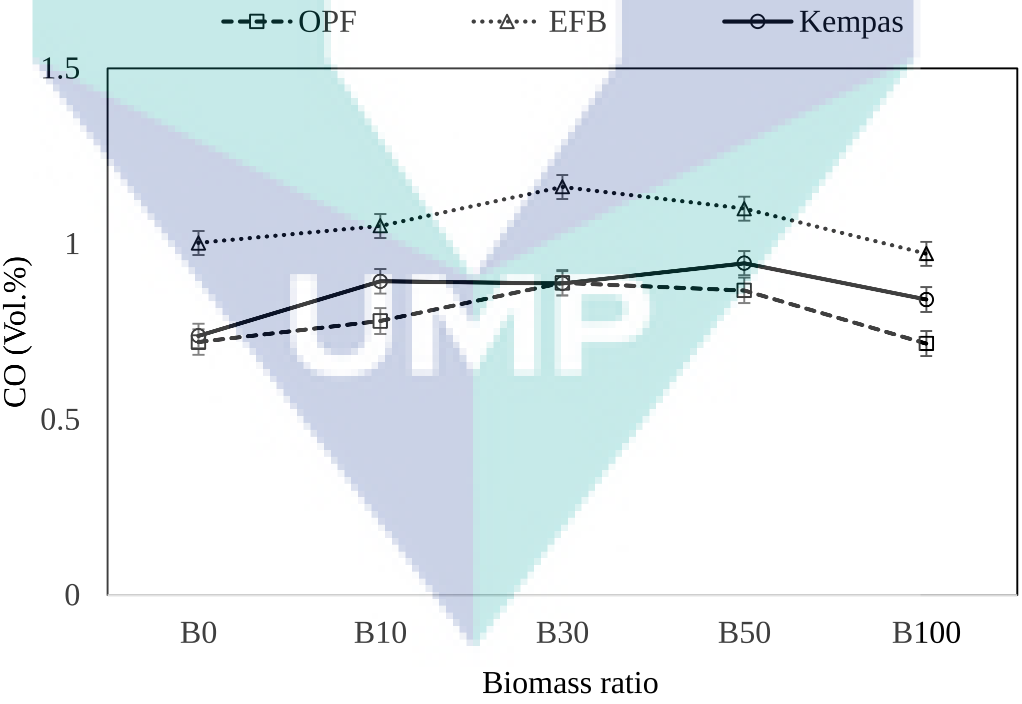


Figure 4.21 CO at various biomass ratios

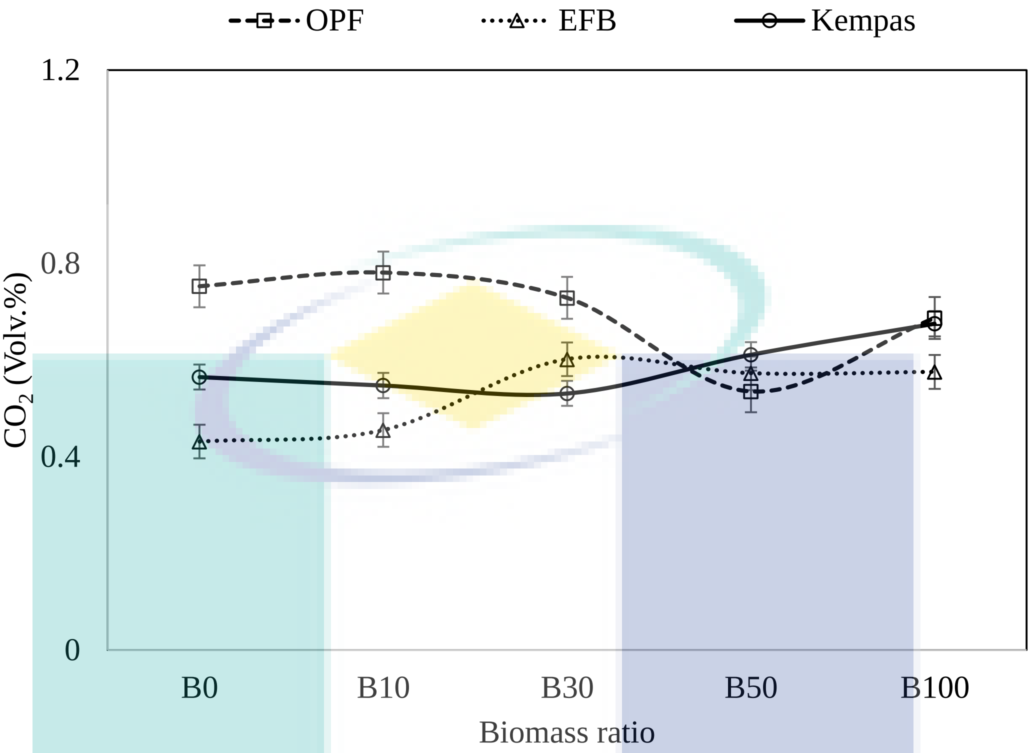


Figure 4.22 CO_2 at various biomass ratios

4.5.2 HHV and CGE for EFB, Kempas, and OPF Co-Gasification

The measures of co-gasification performance in terms of HHV and CGE for the interaction of coal and biomass (EFB, OPF, and Kempas) co-gasification are shown in Figure 4.23 and Figure 4.24, respectively. From Figure 4.23, the HHV slightly increased but then decreased as biomass ratio increased above B30. An increase in CGE was attained due to the higher gas yield and higher HHV (Fermosa et al., 2010). The decrease in HHV is caused by the reduction contents of methane and hydrocarbon as the amount of fixed carbon of coal decreases (Andre et al., 2005). The interactions that occur between the coal and biomass may have been due to the high reactivity of the biomass fuels. When coal is fed into the reactor with biomass, it will react rapidly, releasing a high amount of volatile matter via thermal or oxidative cleavage of the weakest covalent bonds in the organic matter (Lapuerta et al., 2008). Based on Figure 4.24, the CGE slightly increased but then decreased as biomass ratio increased over B30. The decrease in CGE is the result of decreasing of H_2 and CO content along with the decreasing of HHV as mass ratio increases (Hernandez et al., 2010). Synergistic effect of biomass and coal can be seen at biomass ratio 0.5; the gas yield is high at this biomass ratio (Wu et al., 2017). This can be explained by the secondary reactions such as hydrocarbon reforming and WGS reaction (Equation 2.7) that enhance the synergistic effect of the coal and the biomass (Hu et al., 2017).

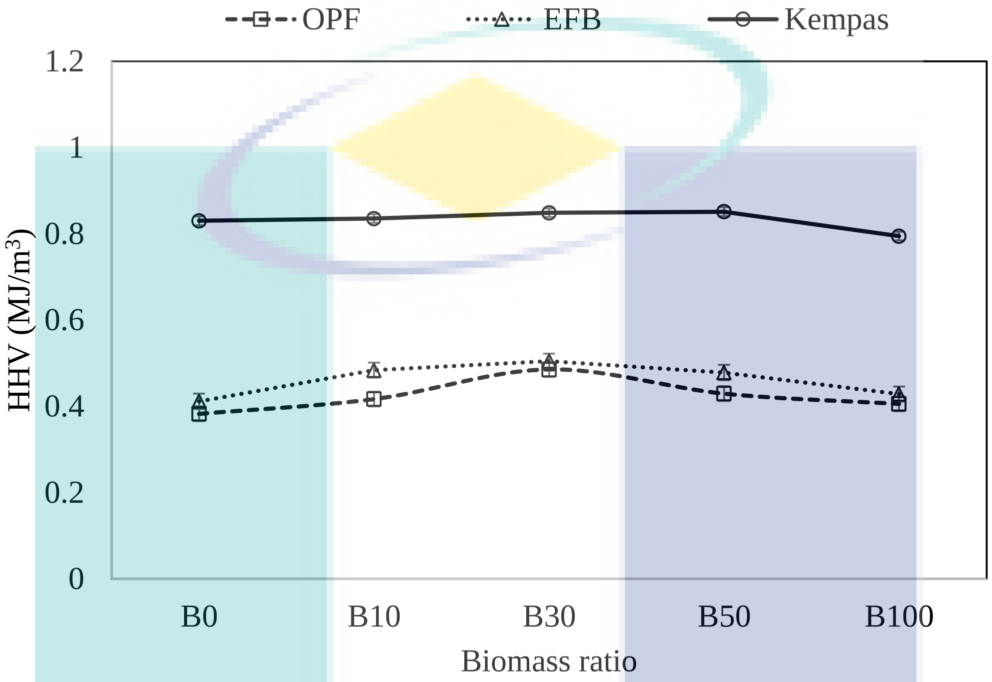


Figure 4.23 HHV at different biomass ratios

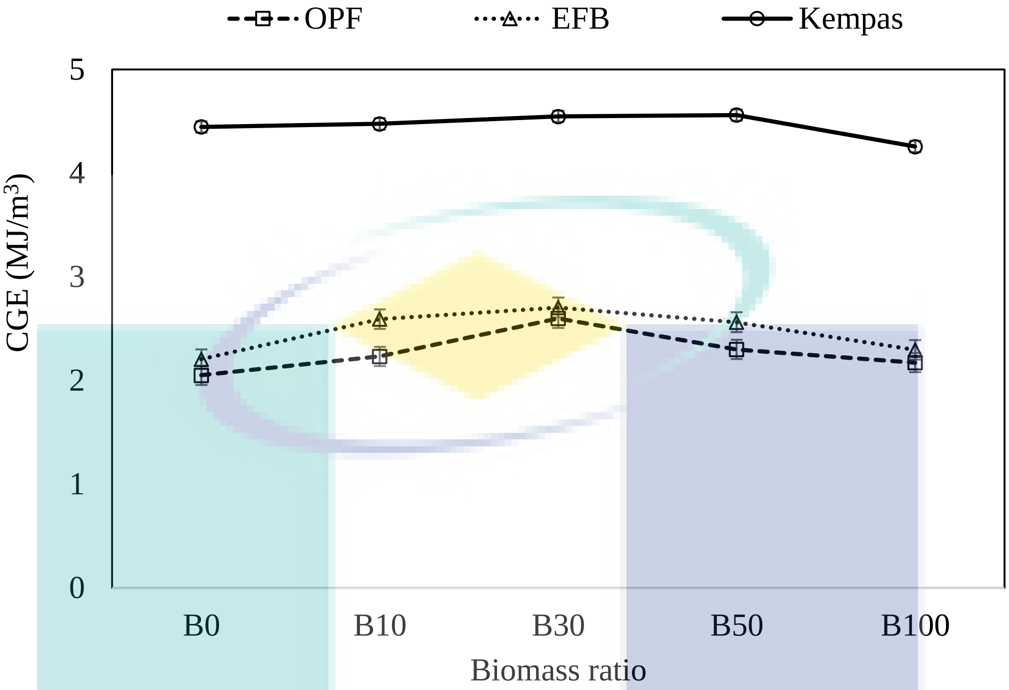


Figure 4.24 CGE at different biomass ratios

CHAPTER 5

CONCLUSION

5.1 Introduction

From this study, temperature, ER, and mass ratio had great influences on syngas production composition, as well as the gasification performances in terms of HHV and CGE. The major findings of this study can be concluded as follows:

i. The temperature and ER highly affects the production of syngas using EFB, OPF, and Kempas in an entrained flow gasifier. The production of H_2 and CO increased while CO_2 decreased as the temperature increased from 700 to 900 °C. Conversely, when the ER was higher than 0.3, the production of H_2, CO, and CO_2 slightly decreased. The production of H_2 for Kempas was significantly higher compared to OPF. Yet, the production of CO and CO_2 were nearly the same for both biomasses. At the temperature of 900 °C, the production of H_2 and CO were the highest. Furthermore, the HHV and CGE achieved their highest values when the temperature was 900 °C and ER was 0.3 for EFB and OPF and 0.35 for Kempas.

ii. For the co-gasification of EFB and Adaro coal, as the biomass ratio increased from B30 to B50 and the temperature was higher than 900 °C, the production of syngas (H_2 and CO) was at its maximum. However, CO_2 production was almost unchanged throughout the temperature and biomass ratio. Additionally, the

iii. biomass ratio of B30 was observed to have the maximum HHV and CGE, which implies the presence of synergistic effects at B30.

iv. The biomass ratio highly affected the product syngas for different feedstocks. The highest amount of syngas was produced at B30, whereas the CO_2 production was the highest at B0. Kempas had the highest H_2 production while EFB had the highest CO production. Similarly, the HHV and CGE for all the sample mixtures also had the highest value at B30, which is another indication of the presence of synergistic effects at B30.

5.2 Recommendations

Considering the results and limitations of this work, further investigation is required to improve the gasification and co-gasification processes. The recommendation for future work are outlined as follows:

- The entrained flow gasifier can be used for temperature higher than 900 °C. Thus, to increase the efficiency as well as syngas products, higher temperature could be applied to this type of gasifier.
- In this thesis, the size of biomass used was fixed for below 250 μm. Using smaller particle size of 210, 150, and 100 μm may help to increase the efficiency of the gasification process.
- Further work should be done to focus on understanding the effects of temperature, ER, and mass ratio on the properties and the production of tar, ash, and other side products formed during gasification and co-gasification process.

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PUBLICATIONS

1. Ismail, W. M., & Rasid, R. A. (2017). Empty Fruit Bunch (EFB) gasification in an entrained flow gasification system. *Chemical Engineering Research Bulletin 19*, 43-49.

2. Ismail, W. M., & Rasid, R. A. (2017). Co-gasification of Coal and Empty Fruit Bunch (EFB) in an entrained flow gasification. *Journal Chemical Engineering and Industrial Biotechnology V2*, 37-46.

3. Ismail, W. M., Rasid, R. A., & Thaim T. M. Biomass Gasification of Oil Palm Fronds (OPF) And *Koompassia Malaccensis* (Kempas) In an Entrained Flow Gasifier: A Performance Study. – submitted to Chinese Journal of Chemical Engineering – Under review.

4. Ismail, W. M., & Rasid, R. A. A Review on The Effect of Temperature and Equivalence Ratio (ER) on Biomass Gasification – submitted to Renewable & Sustainable Energy Reviews - Under review.

5. T. Thaim, R. Abdul Rasid, & W.M.S.W. Ismail. Torrefaction of oil palm fronds (OPF) as potential feedstock for energy production processes. - submitted to Environmental Science and Pollution Research- Under review.

6. Ismail, W. M., & Rasid, R. A. Investigation on the Co-gasification of Coal and Biomass in an Entrained Flow Gasifier: Experimental and Analysis - submitted to Fuel- Under review

7. Utilization of Torrefied OPF for Gasification in an Entrained Flow Gasifier - In preparation.

APPENDIX A
ANALYSIS OF PRODUCT GAS

Calculation for HHV and CGE are shown below:

Higher heating value for EFB for ER = 0.2 at 700 °C:

$$\mathrm{HHV} = \frac{12.76\ \mathrm{H_2} + 12.63\ \mathrm{CO} + 39.76\ \mathrm{CH_4}}{100}$$

$$= \frac{12.75\ (1.112) + 12.63\ (1.0) + 39.82(0.02)}{100}$$

$$= 0.276\ \mathrm{MJ/Nm^3}$$

Similar calculations were performed to calculate HHV for all feedstock

Cold gas efficiency for ER = 0.2 at 700 °C:

$$CGE = \frac{HHV\ of\ product\ gas}{HHV\ of\ fuel} \times 100$$

$$= \frac{0.276}{18.54} \times 100$$

$$= 1.478\ \mathrm{MJ/m^3}$$

Similar calculations were performed to calculate CGE for all feedstock