CHAPTER 1

BACKGROUND

1.1 INTRODUCTION

Nowadays, natural resources such as natural gas and fossil fuels are depleting fast together with the current energy crisis, fluctuating fossil fuel price is a big problem for lots of industrial owner or even shareholder. Companies face bankrupt or zero production due to the unforeseen economy conditions. Biomass is the solution to the problem with the reason that biomass is contributing to the green industries with associated growth in rural economies [2, 8]. As a readily renewable fuel, biomass has become one of the significant components in the global sustainable and environmentally friendly energy. Besides this, it could also be supplied easily compared to others natural resources. Another reason for it is because the price of raw material is much lower compared to the other resources.

Renewable biomass could be readily gasified to produce high purity hydrogen and other gases such as methane, carbon dioxide, carbon monoxide and so on. However, in this project, biomass will be mainly focused on Empty Fruit Bunch (EFB) to produce hydrogen. Hydrogen produced from biomass is a type of clean energy where no net carbon dioxide is being produced. What is the reason for no net carbon? It is because, Palm oil trees need carbon dioxide while Empty Fruit Bunch from palm oil trees may produce carbon dioxide for the tress. With that, carbon dioxide that is being produced is neutral and it could be absorbed again by the plantation of Palm Oil or other plants. Hydrogen also could be readily be used in most of the present natural gas derived hydrogen energy conversion systems and also in advanced power generation devices such as fuel cells. With the forecasted EFB availability around Malaysia per year, 28.46 x 10^6 tons of EFB is being produced per year. This number is equivalent to a total of 8% of Hydrogen world demand which mentioned by Yong et al. While biomass currently contribute 11% of the total world energy supply according to IEA report year 2007.

Gasification produces a product gas from biomass, which could be used either hydrogen or other value-added by-products. Gasification technology is renewed every now and since and it keeps on evolving in order to meet the demand of lowest cost of production and higher production rate. This project focused on integrated pressurized gasification which a technology that has yet been discovered until the time where this report is produced.

1.2 TECHNICAL BACKGROUND

Gasification of biomass is a process used to produce gas from solid biomass. Gasification includes both bio-chemical and thermo-chemical process gasification. Biochemical gasification means gasification by microorganism at normal temperature and pressure while thermo-chemical gasification means using either air, oxygen or steam at temperature more than 800 degree Celsius [1]. In this research gasification will refer to thermo-chemical gasification. In our system, we incorporated carbon dioxide removal unit to enhance the production of hydrogen and to conduct it in high pressure system.

1.2.1 Gasification Reactor Type

Currently found in the industry was the fluidized bed and fixed bed, direct firing and indirect firing, updraft or down draft, or entrained bed and many more. Well in this project, Fluidized bed will be the main concern to be considered into the situation. Section 1.2.2.1 will explain into more detail about fluidized bed.

1.2.1.1 Fluidized bed

The advantages of fluidized bed gasification is the uniform temperature distribution achieved in the gasification zone which is being achieve by using a bed of fine-grained material into which air or steam or air-steam mixture is introduced [1]. Fluidization is to ensure the bed has intimate mixing of the hot bed material, the hot combustion gas and the biomass feed. There are two main types of fluidized bed.

First fluidized bed is the Circulating Fluidized Bed also known as CFB in short. Circulating Fluidized Bed has high throughput and its bed material were circulated between the reactor and cyclone separator. It can be operated in elevated pressure [3].

Second type of fluidized bed is the bubbling bed. It has a grate at the bottom of the moving bed which is used for air intake [1]. The moving bed consists of fine-grained material where feed is being introduced. Bed temperature is being controlled by manipulating the air to biomass ratio.

However, most difficulties faced by fluidized bed is the slagging of bed material due to ash content of biomass. To avoid slagging, temperature has to be lowered down [1]. The gas formed in the gasifier has the below compound:

a. Particulates

   Mostly consist of char. Quantity depends on technology used. Fixed bed produces lesser particulates comparing fluidized bed [1]. Particulates above 10µm can be removed using separator while finer particles require filtering device.

b. Tar

   Tar will be condensed at temperature of less than 450 degree C [1]. Tar can accumulate at the surface of piping and partly remaining as aerosol in the gas. Steam gasification produces liquid tar with low molecular weight. High temperature gasification produces tar at lower oxygen content [1].

c. Nitrogen compound

   Nitrogen is being feed into the gasifier together with air. Content of Nitrogen will dilute the system and lower the productivity.

d. Sulphur compound

   Sulphur compound will damage the catalyst and causes high cost in maintenance and catalyst changing.

e. Alkali compound

   Alkali compound such as Ammonia might form with the presence of Nitrogen and Hydrogen after gasification. This problem might cause effects to the piping system and increase cost of maintenance and operating in the end as ammonia need to be separated again before products can be further used.

Table 1: Pros and Cons of a Fluidized Bed

Advantages	Disadvantages
Flexible feed rate and composition	High product gas temperature
High ash fuel acceptable	High tar and fines content in gas
Able to pressurized	Possibility of high C content in gas
High CH4 in product gas	Operating temperature limited by ash clinkering
High volumetric capacity	
Easy temperature control	

1.2.2 Choices of Gasifying Agent

There are three types of gasifying agent for the gasification of biomass to take place. Air can be used as gasifying agent. Beware that air consist of nitrogen and oxygen at the same time. Nitrogen content in air will dilute the outlet gas and need extra work for separation. Besides separation, nitrogen, as mentioned will cause the formation of some alkaline gas, thus causes some pollution if purged and corrosion might happened at piping system or instrumentation system in the flowsheet.

Next gasifying agent is pure oxygen. Oxygen is mixed together in the gasification unit in order to have the biomass gasify. Pure oxygen may eliminate the problem of nitrogen and ammonia. However producing or purchasing of oxygen may be very expensive.

Another type of gasification agent is steam. Steam can be high in temperature and pressure. Reaction with Empty Fruit Bunch and Steam is a type of endothermic reaction. Endothermic reaction needs heat so that the reaction will run well. It requires heat to be supplied at a temperature around 700 degrees Celsius [1].

1.2.3 Reaction in Integrated Gasifier

Table below shows reactions for gasification unit. In this gasifier, we have carbon gasification reaction, methanation reaction, methane reforming reaction, water gas shift reaction, boudouard reaction, and not to forget, carbon dioxide removal reaction. In carbon dioxide removal system, we use calcium oxide as the catalyst.

Table 2: Reactions in gasification unit

Reaction name	Reaction
Carbon Gasification	$C + H_2O \rightarrow CO + H_2$
Methanation	$C + 2H_2 \rightarrow CH_4$
Methane Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$
Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$
Boudouard	$C + 2CO_2 \rightarrow 2CO$
CO_2 Removal	$CO_2 + CaO \rightarrow CaCO_3$

1.3 PROBLEM STATEMENT

Biomass has been used to produce electricity, steam, petrochemical production and many more industrial purposes. In the current situation, production of Hydrogen from Empty Fruit Bunch using a pressurized system is limited and not being analyzed and developed. Only coal and other gasification feedstock such as rice husk, wood piece and so on are available in the market which uses gasification technology. Thus, this project aims to further develop the gasification process and process flow sheet using Integrated Pressurized Catalytic Fluidized Gasification technology of Empty Fruit Bunch to produce hydrogen gas. This project mainly focuses on the investigation on high pressure gasification using simulation software for better improvement on technology that can be used in order to produce higher yield of hydrogen product at a lower cost.

1.4 OBJECTIVE

The objectives of this project are:

a) To investigate feasible routes to produce Hydrogen from Empty Fruit Bunch at high pressure.
b) To synthesis and develop the feasible route and operating conditions.
c) To develop the flowsheet and restructure to the integrated pressurized catalytic gasification unit in ICON and ASPEN simulation software.
d) To identify the optimum operating conditions.
e) To perform preliminary economic analysis on the flowsheet.

1.5 SCOPE OF STUDY

This project aimed to produce a flowsheet and develop an integrated pressurized catalytic fluidized gasification unit of EFB in iCON simulation. This project also involved investigation and improvement the current technology and feasible route to produce hydrogen from EFB at high pressure. Operating ranges for the project is 0.6MPa to 2MPa for pressure, and temperature range from 1200ºC to 1500ºC while Steam to biomass ratio is analyzed at a ratio of 2 to 3. Gasification agent is steam while absorbent used to absorb carbon dioxide is calcium oxide.

CHAPTER 2
LITERATURE REVIEW AND THEORY

This chapter focused mainly on theory, experiment or project done by other peoples and the stage of developed gasification system and so on. Literature review is to guide and facilitate the understanding of the topic before proceed into the development of simulation for gasification of EFB.

2.1 Empty Fruit Bunch, Cellulose, Biomass

According to the literature by Wang et al, the author mentioned bio-energy from biomass is sustainable and environment-friendly featured by its low emissions of SO_2 and NOx while producing no net Carbon Dioxide [5]. No net Carbon Dioxide in this report means Carbon Dioxide produced will not have any effects to the environment and the green house because Carbon Dioxide that is being gasified is equals to the amount needed by the palm tree. This also means Carbon Dioxide is then being absorbed by the palm oil trees again without polluting the environment.

Maniatis et al. mentioned that biomass is sustainable and environment-friendly featured by its low emissions of alkaline salt while producing no net Carbon Dioxide. This short rotation forestry and other energy crops can contribute significantly towards the objectives of the Kyoto Agreement in reducing the green house gases emissions and to the problems related to climate change [9]. Empty fruit Bunch not only contributing in term of Carbon Dioxide, it also contribute in producing clean gas which is Hydrogen. Hydrogen currently is being used even as a type of fuel for vehicle. Wide usage of Hydrogen causes this project to be feasible.

2.2 Flowsheet simulation on gasifier

Maniatis et al. also presented that, in order to stay competence in the biomass energy conversion market, one must be able to produce something different from the current available technology [9]. Pressurized Integrated Catalytic Gasification may still the feasible one as it has never been developed before and as mentioned by the author we need to be creative with new ideas and development from the previous experience by other researcher. This has added a possibility and opportunity to contribute to the world’s biomass gasification technology.

2.3 Kinetics of gasification

Moilanen et al. observed that steam gasification of peat char presents a rate slightly faster than that observed in Carbon Dioxide environment. For high pressure gasification, kinetics of reaction is hard to be found. The reason is, the technology has not widely being developed yet. In this project of integrated gasification which including the carbon dioxide removal using calcium oxide, reducing Carbon Dioxide at the same time with gasification will eliminate this problem and thus increase its production of hydrogen. Which also means rate of gasification will increase with the decreasing amount of Carbon Dioxide [10].

Matsuoka et al. conducted an experiment using Australian Loy Yng Lignite and Indonesian sub-bituminous Adaro coal. Kinetics of Char Gasification was found for these two different types of char [11].

1. Adaro Coal $k = 1.06 \times 10^{9} P^{0.5}_{(H2O)} \exp(-250000/RT)$
2. Loy Yang Lignite $k = 8.04 \times 10^{9} P^{0.4}_{(H2O)} \exp(-230000/RT)$

This kinetics was put into consideration in our model but at last it was not adapted. The experiment conducted by them was being run through in a high pressure gasifier of 0.2MPa, and 0.5Mpa. At the same time, another experiment also being run under high pressure but at different temperature. Temperature also has impact in this case.

From one of the figure published, the rate of gas formation is very low at the operating pressure of 0.5MPa and temperature at 1046K. While for another figure published, with the operating pressure of 0.5MPa and temperature of 1114K, the product yield reaches a peak within less than 500 seconds. This is a great figure to prove that hydrogen production is applicable in high pressure system. However, when compare the above mentioned figure to the third figure in the paper, which operates at 0.2MPa and 1123K, we found that the hydrogen also yield although the peak but it is not as sharp as the one in the second figure. However, the amount is about the same. With these, it is concluded by them that high pressure gasification system does not have significant effects on the hydrogen yield. This statement is then supported by another literature by Mahishi et al. [13].

2.4 Pressurized gasification

Wang et al., mentioned pressurized gasification system with hot gas cleaning is an advance concept, which can provide higher efficiency and have less serious tar issues [5]. However, according to an online paper (no author name mentioned), at gasification conditions 825ºC and 2 MPa, tars, chars, and volatile alkalis are generated [6]. The reason might due to probably due to the low temperature for tar formation. Usually a gasification unit will work at high temperature. For simulation purposes, tar issues will not be considered.

Fermoso et al. reported that an increase in pressure was observed to produce a slight increase in Methane and Carbon Dioxide to the detriment of Hydrogen and Carbon Monoxide, as the increase in pressure shifts the equilibrium to the side with the fewer moles of gas (equations below). The same tendencies were observed when the equilibrium gas composition was calculated by varying the total pressure [12].

Steam Reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$,

Dry Reforming: $CH_4 + CO_2 \rightarrow 2CO + 2H_2$

With this, we can come to a small conclusion that, high pressure really can cause decrease in Hydrogen yield but prove needs to be done in order to have the appropriate explanation. As form one of the figure in their paper, we can analyze that Hydrogen yield decreased while Carbon Monoxide and Methane increases. However, in our project, this phenomenon might help us when it comes to methane reforming in the later part of the reactions as we can break up the CH_4 bone and get more Hydrogen from there.

Fiaschi et al. however mentioned that, bed temperature increases with pressure causing Boudard reaction shift to the left and leads to overall reduction in gasification process. Char conversion ratio versus pressure shows an optimized value of 5bar. (Maximum Carbon Monoxide and Hydrogen and minimum Carbon Dioxide & Methane observed)

From this, it can be noticed that the temperature they used are too high. So this might cause their operating parameters different from us. With that, 5bars is just a reference as our operating temperature is different.

Mahishi et al.’s experiment has proven that effects of pressure will reduce the rate of Hydrogen production. As pressure increases, the equilibrium Hydrogen and Carbon Monoxide yields reduce. Simulation has been carried out to prove the statement and it was found that if the reaction were to be under pressure, the change in Hydrogen yield is negligible even for pressure at 0.1atm [13]. From this statement and table above, they have proven that Hydrogen is not increasing with pressure but decreasing.

2.5 Economics

According to this article by a group of technical specialist from California (name not mentioned), Indirect heating plus pressurized operation, results in smaller gas volumes and much smaller equipment. Even though this results in higher unit costs of high-pressure vessels and piping, but the overall effect is lower total equipment costs [7]. This could not be concluded yet as their product might be different from ours as we need only Hydrogen and they probably need methane or other product which is higher in price to cover back their losses in capital cost for pressurized system. However, this could be used as a guideline for this project.

Maniatis et al.’s article also commented on economics part regarding biomass gasification. Gasification technologies have recently been successfully demonstrated at large scale and several demonstration projects are under implementation, they are still relatively expensive in comparison to fossil based energy and, therefore, new entrants may have to face economic and other non-technical barriers when trying to penetrate the energy markets [9].

Lau et al. in their article mentioned that a pressurized plant with all the equipment being pressurized, high equipment wear and higher power consumption need to be considered. Cost of purchasing or maintenance can be quite high when times come [14]. This has to add into consideration of this project when comes to economics evaluation.

Besides all the above, Maniatis et al. also commented about pressurized fluidized bed system in this paper mentioned above. According to the paper, pressurized fluidized bed systems are considered of medium market attractiveness due to the more complex operation of the installation and to the additional costs related to the construction of all pressurized vessels. Pressurized systems have been proposed mainly by CARBONA and FOSTER WHEELER with the successful application of SYDKRAFT's Värnamo IGCC (Sweden) [9]. In my personal opinion, product selling can conclude a plant's profit and its rate of return for the investment on the capital cost of the plant. If our product, Hydrogen is not selling high, we might end up losses in term of money or on the other hand if our product, hydrogen is selling well, it will be the best gasification unit on earth.

All and all, it depends on what we sell as our product in order to cover the capital cost and operating cost of this biomass gasification plant. We could draw a small conclusion that, the operating cost must be considered importantly as it might cause the project to lose money or from another aspect gaining profit as we supply to a plant which causes the plant cut cost in purchasing Hydrogen as their feedstock.

2.6 Research by other author

As addition to the above information, Hanaoka et al. conducted a gasification experiment at high pressure using woody biomass and steam together, incorporated with the carbon dioxide removal unit. They reported that at pressure of 0.6-0.7MPa, hydrogen yield increases with temperature. The highest hydrogen yield is predicted at 0.6MPa. Hanaoka et al. is a good reference for this project as it provides us a platform to develop and compare the simulated empty fruit bunch simulation result [23].

In addition, Florin et al. [22] investigated on a system of gasification combined with carbon dioxide removal. Based on their results, they reported that hydrogen yield is increasing with temperature. Hydrogen yield also poses the same trend of increment corresponding to the steam-to-biomass ratio. Meanwhile, overall hydrogen production is observed to increase with its pressure.

Since the hydrogen production from biomass via pressurized gasification that is coupled with carbon dioxide adsorption has not been widely investigated and there are limited models to represent the case, this paper hence focus to develop such system and predict its performance via a simulation approach. In this work, a simulation model is developed in PETRONAS iCON process simulator and is used to investigate the technical feasibility of the biomass pressurized gasification system based on the effect of parameters such as pressure, temperature and steam-to-biomass ratio on the hydrogen yield.

CHAPTER 3
METHODOLOGY

3.1 RESEARCH AND ANALYSIS TECHNIQUE

Research technique in this Final Year Project 1 will mainly based on journals, conference, paper, reports and reliable source on the internet or e-book at the same time communicate with the project team for the previous research done.

3.2 FLOWCHART

This project first focused on understanding of the topic and the relevancy to the current biomass technology - gasification. This include reviewing previous material which inclusive of journals, previous reports, conference papers and articles on gasification of biomass and types of gasification that has been developed and used in the current time and date and those has yet been developed.

After the literature review and understanding of the whole concept of the project, it is then moved on to evaluation and detailed analysis on other people's work and achievements while identify the temperature and pressure. The project is then being continued by including modifications and developing a process flow sheet which focused on integrated pressurized catalytic fluidized gasification reactor. There are three cases of which is to be investigated. Firstly, biomass is referred to carbon only but at both high pressure and atmospheric pressure. After that, kinetic of EFB was being identified and incurred into the atmospheric system. With that, preliminary block diagram was developed and process simulation was used to identify the flow and operating conditions of the gasification.

After the simulation has been completed, this project runs through a system performance analysis to enhance the system's parameter to identify whether there is some improvement or betterment to be done.

Lastly, the project will go through an economic evaluation to identify the feasibility of the project to be applied in the real industrial world. Please refer to figure 1 for better understanding of the simplified process flow.

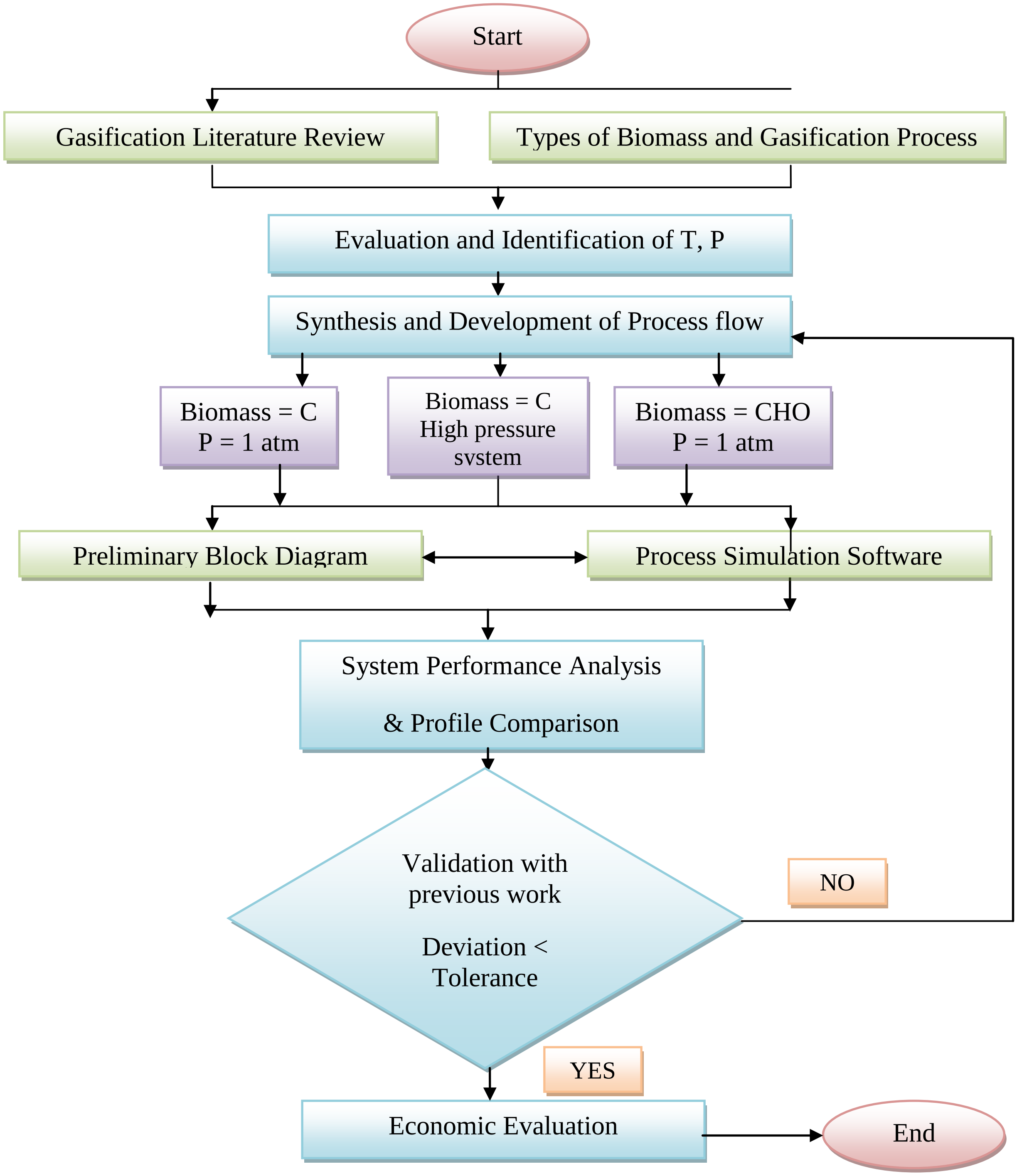


Figure 1: Flowchart on process of project

3.3 TOOLS / SOFTWARE REQUIRED

a. ICON Simulation Software
b. ASPEN Simulation Software

As this project mainly relates about modeling, both ICON and ASPEN Simulation Software can be used to compare the accuracy and the adaptability of this modeling results. Comparison may assist in the project modeling accuracy.

3.4 GANTT CHART

Semester	**Semester 1**				**Break**	**Semester 2**			
Period	**1/4**	**2/4**	**3/4**	**4/4**		**1/4**	**2/4**	**3/4**	**4/4**
To Investigate feasible routes to produce Hydrogen from Empty Fruit Bunch	🟩	🟩	🟩						
Synthesis and develop the feasible route and operating conditions via process simulation software			🟦	🟦					
Develop flowsheet and restructure to the integrated pressurized catalytic gasification unit using Aspen and Icon					🟥				
To identify optimum operating conditions						🟪	🟪		
To perform economic analysis								🟧	🟧

Figure 2: Gantt Chart representation on progress of project and task accomplishment and deadlines.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 CASE 1: Biomass was represented by C at high pressure gasification.

In result and discussion, this chapter will mainly discuss about the findings at Chapter 2, literature review and the results of simulation. In this section until the time being, all simulation results are based on an assumption of EFB is represented by Carbon only.

As from the literature review, most of the research team start the flowsheeting work by dividing the plant into three section namely feedstock processing, gasifier or gasification reactor, and last part is purification before Hydrogen is being produced. In order to start the simulation, reactions must be known and finalized before proceed to kinetic researched.

4.1.1 Reactions in Integrated gasification unit

Before a gasification unit needs to operate, we must first know the reaction in the gasification unit. From Chapter 1 in this report, we understand that there are six reactions to be researched. All of the abovementioned reactions do has its own enthalpy. Table below shows that the researched enthalpy of each particular reaction and its references.

Table 3: Reactions and its enthalpy (Case 1)

Reaction name	Reaction	ΔH (kJ/mol)	Ref.
Carbon Gasification	$C + H_2O \rightarrow CO + H_2$	131.5	[16, 17]
Methanation	$C + 2H_2 \rightarrow CH_4$	-74.8	[16]
Methane Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$	206	[16, 18]
Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41	[16, 17, 18]
Boudouard	$C + 2CO_2 \rightarrow 2CO$	172	[16]
CO_2 Removal	$CO_2 + CaO \rightarrow CaCO_3$	-178	[17, 18]

4.1.2 Kinetic Research

After knowing the reactions, the project now focused on the research on kinetics. Table below shows the kinetic applied in the simulation software to identify the results of pressurized gasification of biomass.

For gasification of biomass, kinetics was adapted from Lv et al. [21]. Reason to adapt the kinetics from there is because Lv et al. has the same kinetics of methanation with Biba et al. which their reported operating pressure is set to 2.648Mpa [19]. Since Biba et al. reported high pressure kinetics, Lv et al. is assumed to report in high pressure too. Raman et al. is also having the same kinetics as Biba et al. but no pressure parameters were being mentioned in Raman text [20].

Methanation reaction, Biba et al, Raman et al. and Lv et al. has the same value [19, 20, 21]. However, as mentioned above, only Biba et al. has the pressure parameter of 2.648Mpa. Other author did not mention about pressure parameters. With this, the kinetics has been adapted for this investigation.

Next, bouduard reaction’s kinetic was also adapted from Biba et al with the reaction pressure of 2.648Mpa and the kinetics is the same as the one published by Raman et al [19, 20].

Lv et al. with no pressure parameter specify, has the same kinetics value for methanation as well as water gas shift reaction which published by Biba et al. and Raman et al. [19, 20, 21]. With that, methane reforming’s kinetic is adopted from Lv et al. since Biba et al. and Raman et al. did not mention about kinetic value for methane reforming.

While for water gas shift reaction, Lv et al., Biba et al. and Raman et al. has the same kinetic value. This kinetic is considered as the kinetic of reaction for high pressure system in this case as Biba et al. mentioned about 2.648Mpa for their modeling [19, 20, 21].

Carbonation kinetic was adapted from Lee et al. which the operating pressure reported are 3, 7, and 15 bar.

Table 4: Kinetics research on reactions for gasification (Case 1)

Reaction	Kinetics	Reference	Basis
Gasification	$1.05 \times 10^7 \exp(-232000/RT)$	PengMei LV et al. (2008)	Wood Powder
Methanation	$21 \times 10^3 \exp(-230274/RT)$	Vaciav Biba et al. (2002)	Coal
		Pattabhi Raman et al. (2002)	Feedlot Manure
		PengMei LV et al. (2008)	Wood Powder
Bouduard	$2.0 \times 10^7 \exp(-360065/RT)$	Vaciav Biba et al. (2002)	Coal
		Pattabhi Raman et al. (2002)	Feedlot Manure
Methane reforming	$7.0 \times 10^3 \exp(-30000/RT)$	PengMei LV et al. (2008)	Wood Powder
WGS	$1.0 \times 10^7 \exp(-12560/RT)$	Vaciav Biba et al. (2002)	Coal
		Pattabhi Raman et al. (2002)	Feedlot Manure
		PengMei LV et al. (2008)	Wood Powder
Carbonation	$96.34 \exp(-101189/RT)$	Duek Ki Lee et al. (2003)	Methane + Steam

4.1.3 Process Assumptions

Assumptions made regarding the gasification of biomass are listed below:

1. Biomass is assumed to be carbon, C.
2. Gasification unit is assumed to be in adiabatic condition.
3. Carbonation is assumed to be forward reaction only.
4. Ash will not participate in the reaction (assume to be inert).

4.1.4 Process flow explaination

Firstly, feed is being treated and pelletized before it is being fed into the gasification unit. The whole process of gasification is assumed to be happened in the gasification unit that coupled with the Carbon Dioxide Removal unit. Reaction happens in the gasification include Carbon Gasification, Methanation, Methane Reforming, Water Gas Shift, and Bouduard. Carbon Dioxide Removal was then coupled outside of the gasification unit. However, in this paper, both of the unit is assumed to be combined in order to simulate for the result. After the Carbon Dioxide Removal, the product gas is then being fed into the Pressure Swing Adsorption (PSA) unit to eliminate the remaining gas. Figure below shows the iCON simulation software layout of the gasification process coupled with carbon dioxide removal unit while another figure shows the table representation from one of the iCON analysis.

4.1.5 Effects of Steam to Biomass ratio

From the simulation, steam to biomass ratio effects towards hydrogen yield was being investigated. Figure below shows the mass percent of product gas versus steam to biomass ratio. From the result, hydrogen product from the end of the production line is decreasing with increase steam to biomass ratio. According to Florin et al., steam to biomass will increase hydrogen yield [22]. The reason being is because carbon or biomass in this case has fully reacted in the earlier part of gasification reaction and methanation. Since steam is water at high temperature, the more water being feed into the system, the less concentrated hydrogen is as at the temperature and pressure, provided gasification reactions do not react further as water has been fed in with enough quantity at first to have the reaction of carbon to complete. With this, increasing steam to biomass ratio is concluded to increase the hydrogen yield provided enough carbon remains in the gasification. Here, we define hydrogen yield as amount of hydrogen produced over amount of biomass fed (in kgs). With the same analysis, hydrogen yield increases with increasing steam to biomass ratio. Figure 5 shows the graph of hydrogen yield over steam to biomass ratio. According to Florin et al. and Mahishi et al., both agree with increase hydrogen yield with increasing steam to biomass ratio. Reason being the increment is because of the forward reaction of water gas shift reaction.

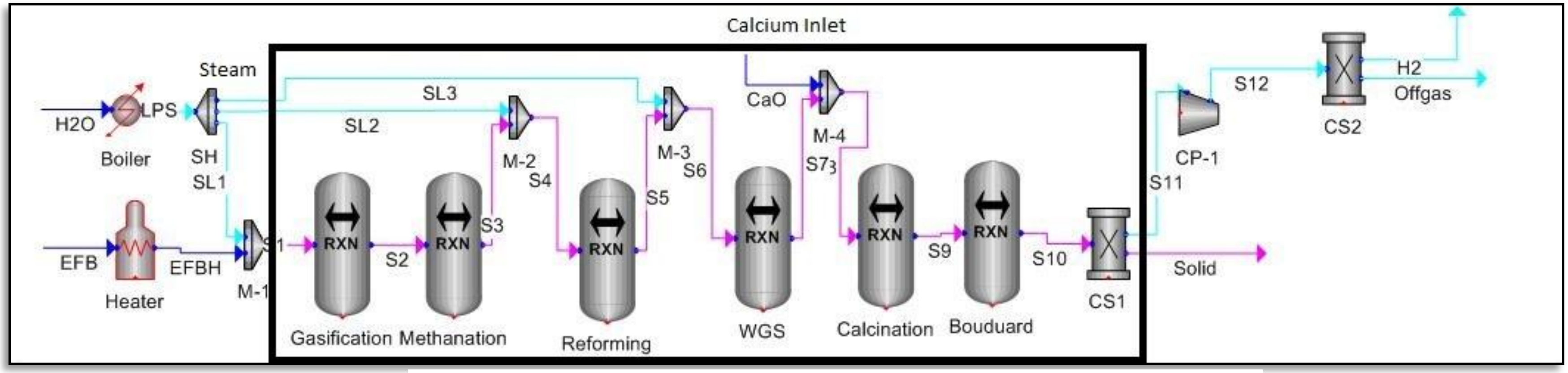
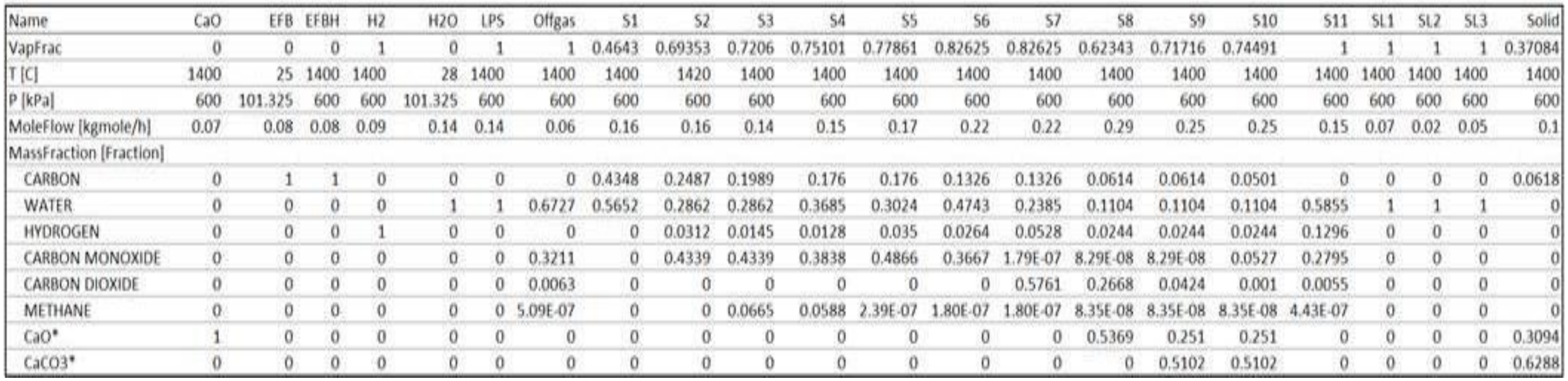


Figure 3: iCON simulation software interface

Figure 4: Table adaptation from iCON simulation software



Name	CaO	EFB	EFBH	H2	H2O	LPS	Offgas	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	SL1	SL2	SL3	Solid
VapFrac	0	0	0	1	0	1	1	0.4643	0.69353	0.7206	0.75101	0.77861	0.82625	0.82625	0.62343	0.71716	0.74491	1	1	1	1	0.37084
T [C]	1400	25	1400	1400	28	1400	1400	1400	1420	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
P [kPa]	600	101.325	600	600	101.325	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
MoleFlow [kgmole/h]	0.07	0.08	0.08	0.09	0.14	0.14	0.06	0.16	0.16	0.14	0.15	0.17	0.22	0.22	0.29	0.25	0.25	0.15	0.07	0.02	0.05	0.1
MassFraction [Fraction]																						
CARBON	0	1	1	0	0	0	0	0.4348	0.2487	0.1989	0.176	0.176	0.1326	0.1326	0.0614	0.0614	0.0501	0	0	0	0	0.0618
WATER	0	0	0	0	1	1	0.6727	0.5652	0.2862	0.2862	0.3685	0.3024	0.4743	0.2385	0.1104	0.1104	0.1104	0.5855	1	1	1	0
HYDROGEN	0	0	0	1	0	0	0	0	0.0312	0.0145	0.0128	0.035	0.0264	0.0528	0.0244	0.0244	0.0244	0.1296	0	0	0	0
CARBON MONOXIDE	0	0	0	0	0	0	0.3211	0	0.4339	0.4339	0.3838	0.4866	0.3667	1.79E-07	8.29E-08	8.29E-08	0.0527	0.2795	0	0	0	0
CARBON DIOXIDE	0	0	0	0	0	0	0.0063	0	0	0	0	0	0	0.5761	0.2668	0.0424	0.001	0.0055	0	0	0	0
METHANE	0	0	0	0	0	0	5.09E-07	0	0	0.0665	0.0588	2.39E-07	1.80E-07	1.80E-07	8.35E-08	8.35E-08	8.35E-08	4.43E-07	0	0	0	0
CaO*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5369	0.251	0.251	0	0	0	0	0.3094
CaCO3*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5102	0.5102	0	0	0	0	0.6288

As more water is being fed into the reaction and the carbon or biomass has finish reacted, increasing amount of water will cause a forward reaction to the water gas shift reaction too. With this, an increasing amount of hydrogen is noticed.

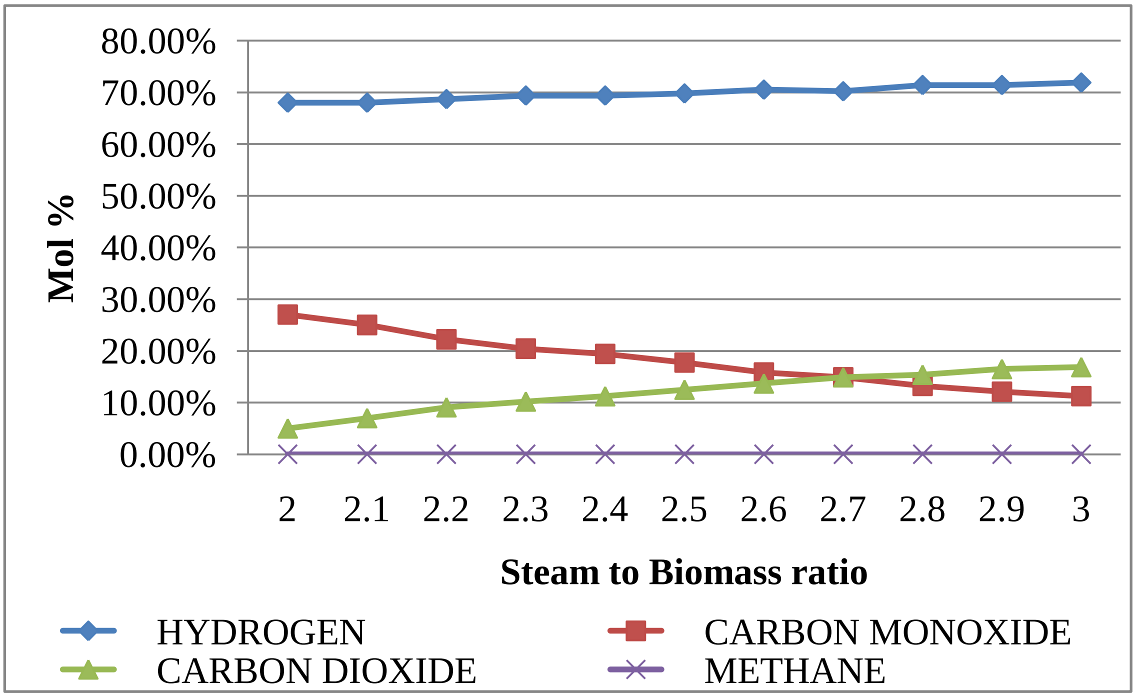


Figure 5: Effects of mol percent on steam to biomass ratio (Case 1)

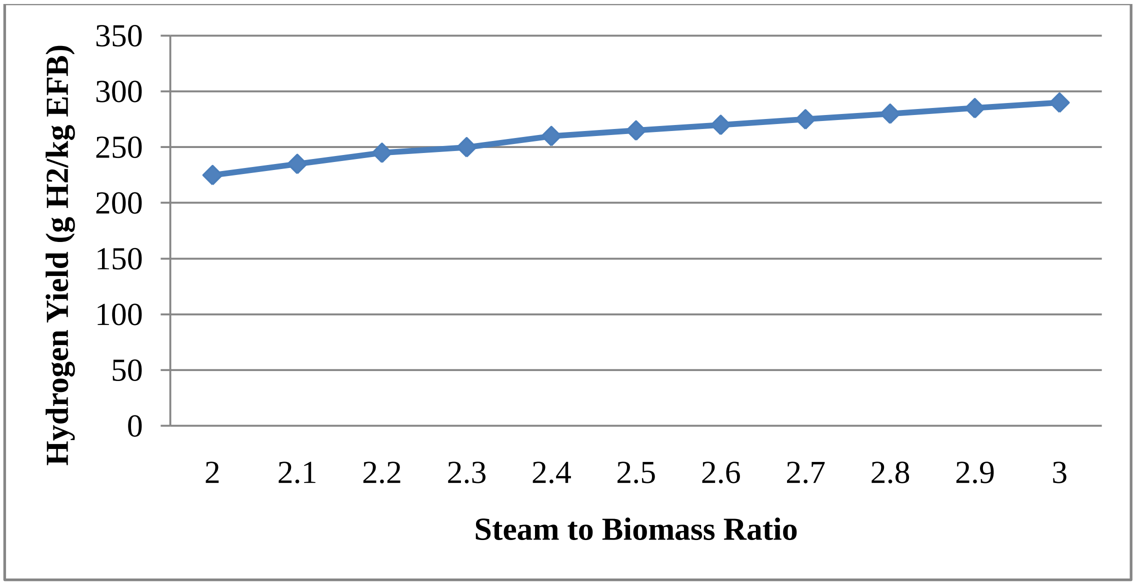


Figure 6: Effects of hydrogen yield on steam to biomass ratio (Case 1)

4.1.6 Effects of Pressure

In order to simulate the effects of pressure, steam to biomass ratio and temperature is fixed. After simulate, hydrogen percentage were found to be in the increasing trend with pressure. This was also reported in the paper by Florin et al. Reason for the increment is because of the integrated system where all the reactions were combined and assist by the carbon dioxide removal unit. Carbon dioxide that produced in the reactions will cause dilution on the hydrogen component in the product gas. After removing carbon dioxide, hydrogen composition increases in the product gas. This can conclude that, the mixture of reactions mentioned in Table I can really increase the hydrogen yield. Figure below shows hydrogen increases with pressure while carbon monoxide decreases and the result shows none of the carbon dioxide. Second figure below shows hydrogen yield increase with pressure. This increase is only noted at 1 percent. In other hand, the increment of hydrogen production over a fixed amount of biomass is said to be negligible. This is also reported by Mahishi et al.

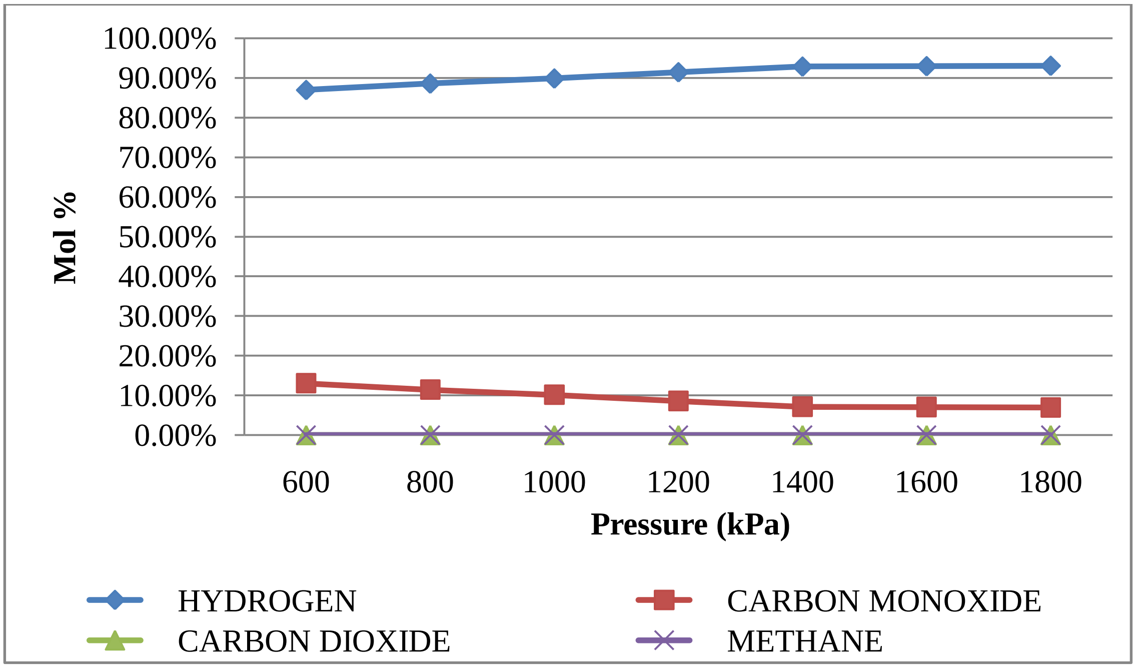


Figure 7: Effects of mol percent on pressure (Case 1)

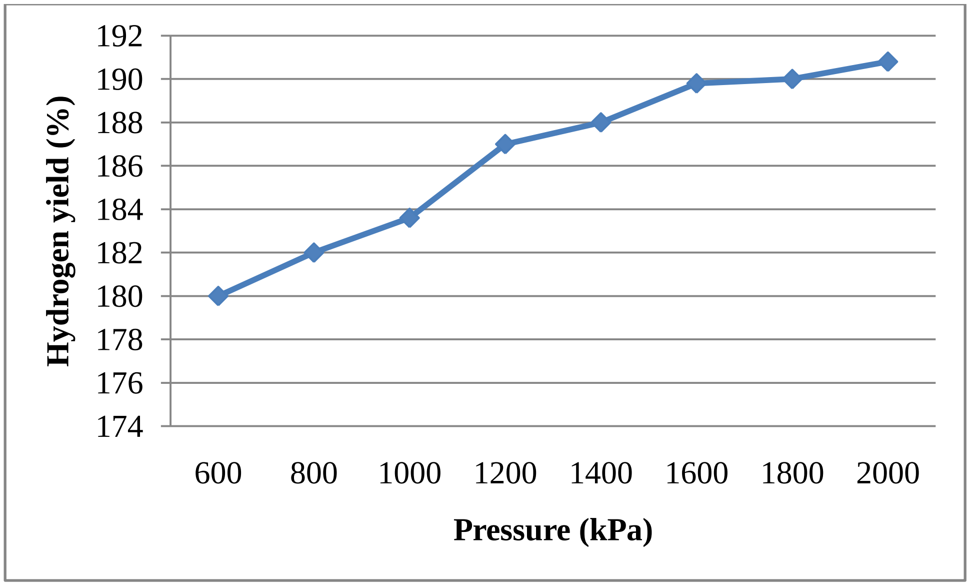


Figure 8: Effects of hydrogen yield on pressure (Case 1)

4.1.7 Effects of Temperature

In term of temperature, for high pressure gasification system, Hydrogen product increases with increasing temperature. This was supported by the paper published by Hanaoka et al. in the year 2005[23]. It was then mentioned too in another paper by Fermoso et al. about the statement of hydrogen product increase with temperature [12].

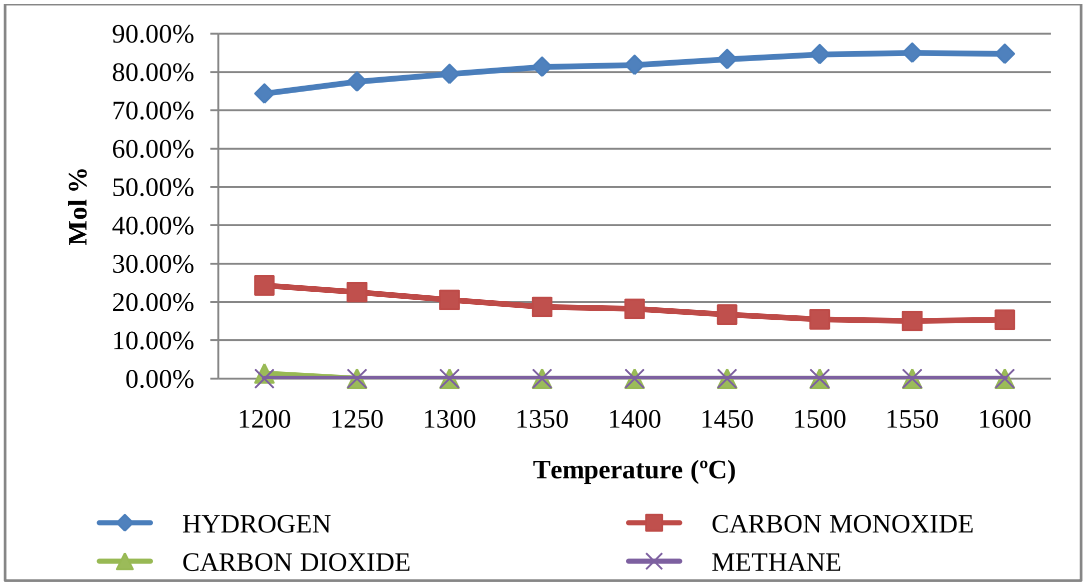


Figure 9: Effects of mol percent on temperature (Case 1)

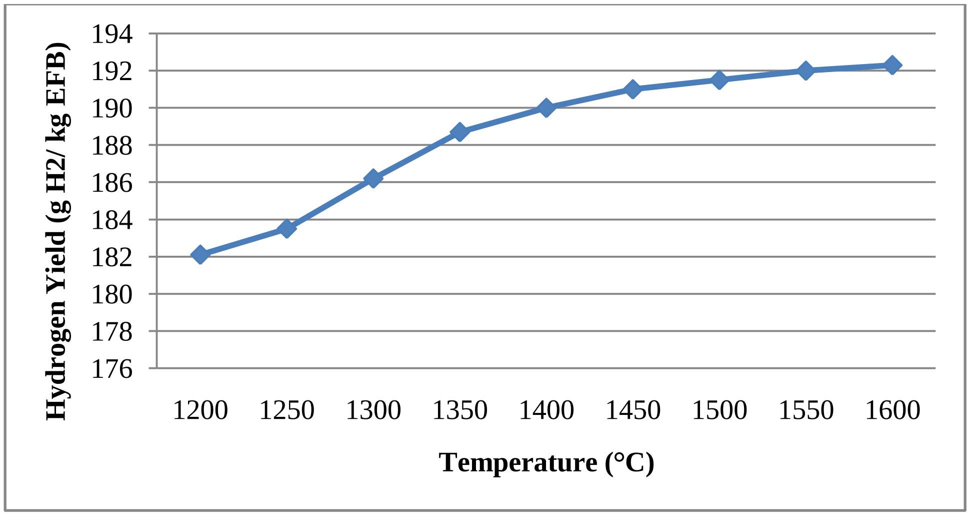


Figure 10: Effects of hydrogen yield on temperature (Case 1)

Reason for increasing hydrogen product when increasing temperature is because when temperature increases, carbon tends to react with carbon dioxide more and produces more carbon monoxide. With this, carbon monoxide then can react with more water (steam) to produce more hydrogen. Since all of this happens in a gasification unit, this reaction is repeated and more hydrogen product is produced. The production of methane is constant with increasing temperature which is also mentioned by Fermoso et al [12]. Another figure below illustrate the effects of mass percent of hydrogen and other components on temperature while figure below shows the effects of hydrogen yield on temperature.

4.2 CASE 2: Biomass was represented by C at atmospheric pressure gasification.

In result and discussion of case 2, it will mainly discuss about the findings from the simulation. In this section until the time being, all simulation results are based on an assumption of EFB is represented by Carbon only and the whole system is to be in atmospheric pressure.

As from chapter 2 not much literature review has been done for this part due to time constraint as this task is a side task (beside the main task – high pressure gasification). However, most of the research team too starts with the flowsheeting work by dividing the plant into three sections namely feedstock processing, gasifier or gasification reactor, and last part is purification before Hydrogen is being produced. In order to start the simulation, reactions must be known and finalized before proceed to kinetic researched.

4.2.1 Reactions in Integrated gasification unit

Before the gasification unit needs to be operated, we must first know the reaction in the gasification unit. From Chapter 1 in this report, we understand that there are six reactions to be researched. The abovementioned reactions do has its own enthalpy. Table below shows that the researched enthalpy of each particular reaction and its references.

Table 5: Reactions and its enthalpy (Case 2)

Reaction name	Reaction	ΔH (kJ/mol)
Carbon Gasification	$C + H_2O \rightarrow CO + H_2$	118.9
Methanation	$C + 2H_2 \rightarrow CH_4$	-74.8
Methane Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$	222.35
Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	-42
Boudouard	$C + 2CO_2 \rightarrow 2CO$	172
CO_2 Removal	$CO_2 + CaO \rightarrow CaCO_3$	-170.5

4.2.2 Kinetic Research

As from research, it is found that the kinetics were totally different from the kinetics of high pressure system. Gasification was adapted from Corella J et al. [26] and Gonzalez et al. [27] Both of them have the same agreed kinetics for the system. Next, methanation, we have Choi Y. C et al. [28] and Govin R. et al. [29] agreed with the same kinetics. From this case, we can surely adapt the kinetic as they were being agreed upon. While for Bouduard reaction, we have two different author (Choi Y. C et al. [28] and Brown B.W. et al. [30]) agreed at the same kinetic too while they were using different kind of feedstock for their process. Methane reforming is another reaction which agreed by four authors namely, Corella J. et al., [26] Therien N. et al., [31] Liu

H. et al., [32] and Fletcher D. F. et al. [33] while Corella J. er al., [26] Gonzalez et al., [27] Xu J. et al., [34] and Simell P. A. et al. [35] agreed with the same kinetic for the water gas shift reaction. For carbonation, we have Irfan A. et al. [36] with the feedstock of pure carbon dioxide and Milne B. W. et al.[37] with the feed stock of biomass to agree together on the same kinetic as of tabled below.

Table 6: Kinetics research on reactions for gasification (Case 2).

Reaction	**Kinetics**	**Reference**	**Basis**
Gasification	$2.0 \times 10^5 \exp(-600/T)$	[26] , [27]	Biomass
Methanation	$0.12 \times 10^3 \exp(-1792/T)$	[28] , [29]	Coal
Bouduard	$4.4 \times 10^3 \exp(-1.62 \times 10^3/T)$	[28]	Coal
		[30]	Biomass
Methane reforming	$3.1005 \exp(-1500/T)$	[26] , [31] , [32] , [33]	Biomass
WGS	$1.0 \times 10^6 \exp(-6370/T)$	[26] , [27] , [34] , [35]	Biomass
Carbonation	$10.2 \times 10^6 \exp(-44.5/T)$	[36]	Pure CO_2
		[37]	Biomass

4.2.3 Process Assumptions

Assumptions made regarding the gasification of biomass are listed below:

1. Biomass is assumed to be carbon, C.
2. Gasification unit is assumed to be in adiabatic condition.
3. Carbonation is assumed to be forward reaction only.
4. Ash will not participate in the reaction (assume to be inert).

4.2.4 Process Description

All process descriptions are as of above in section 4.1.4. Please refer above for accuracy of each analysis performed. However, in this case, we will mainly focus on atmospheric pressure and assuming Empty Fruit Bunch as Carbon only.

4.2.5 Steam to Biomass ratio

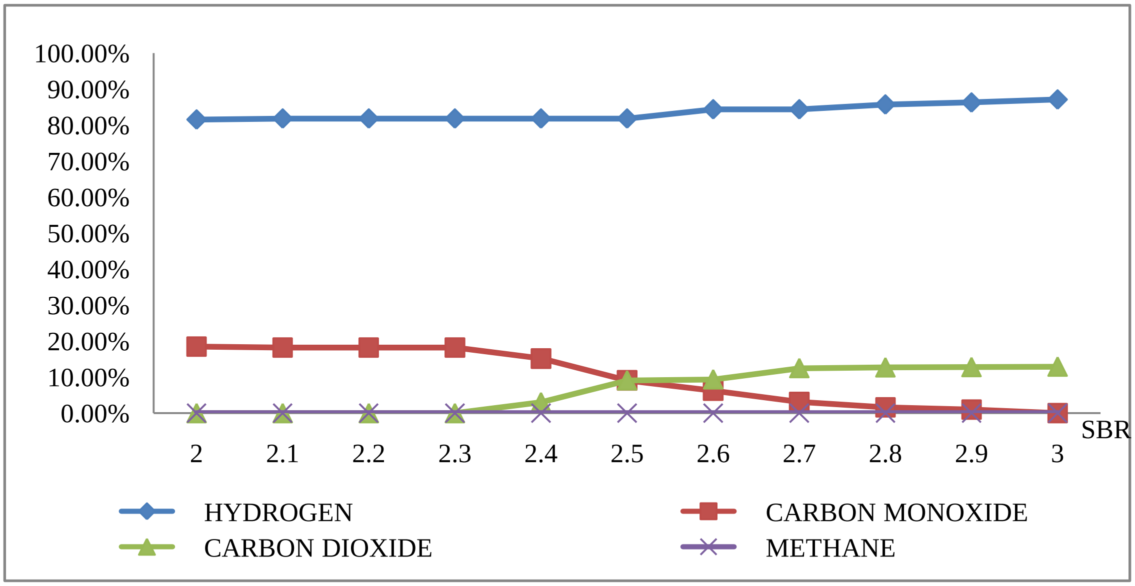


Figure 11: Effect of Steam to Biomass ratio on product gas composition (Case 2)

Figure 11 shows the effect of steam to biomass ratio from two – three at a specific temperature of 850°C at atmospheric pressure condition. The plot shows that the production of hydrogen as main product gas increases from around 80% to 86% and almost constant after that point. Trend for methane were zero-ed all the time while carbon monoxide decrease from around 18% to almost zero. Carbon dioxide in the increasing trend after steam to biomass ratio increases to 2.3. Carbon monoxide and carbon dioxide plots were inverses to each other explaining the effect of water gas shift reaction which more steam available to convert carbon monoxide to carbon dioxide and hydrogen. The optimum steam-to-biomass ratio that can be predicted from plot in Figure 3 is 2.4 that also match the theoretical-stoichiometric ratio. Mahishi et al. [13] and Gao et al. [41] reported that suitable steam-to-biomass ratio of biomass gasification is 3 and 2.05 respectively, which close to the finding of this study i.e. 2.4.

4.2.6 Pressure

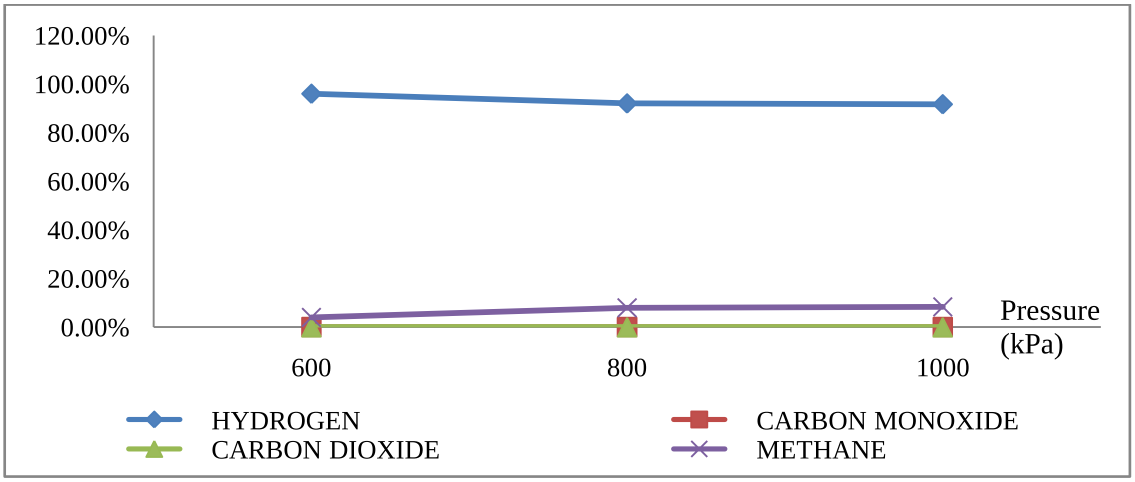


Figure 12: Effect of pressure on product gas composition (Case 2)

As from the graph, we can see that hydrogen is around the range of 80% while methane is around 0% to 10%. When pressure increases, hydrogen production will decrease. The finding only reaches a pressure of 100°C only as the simulation went un-converged after that. The main reason might be due to the kinetics which is not suitable to be applied in a high pressure situation of more than 1MPa.

4.2.7 Temperature

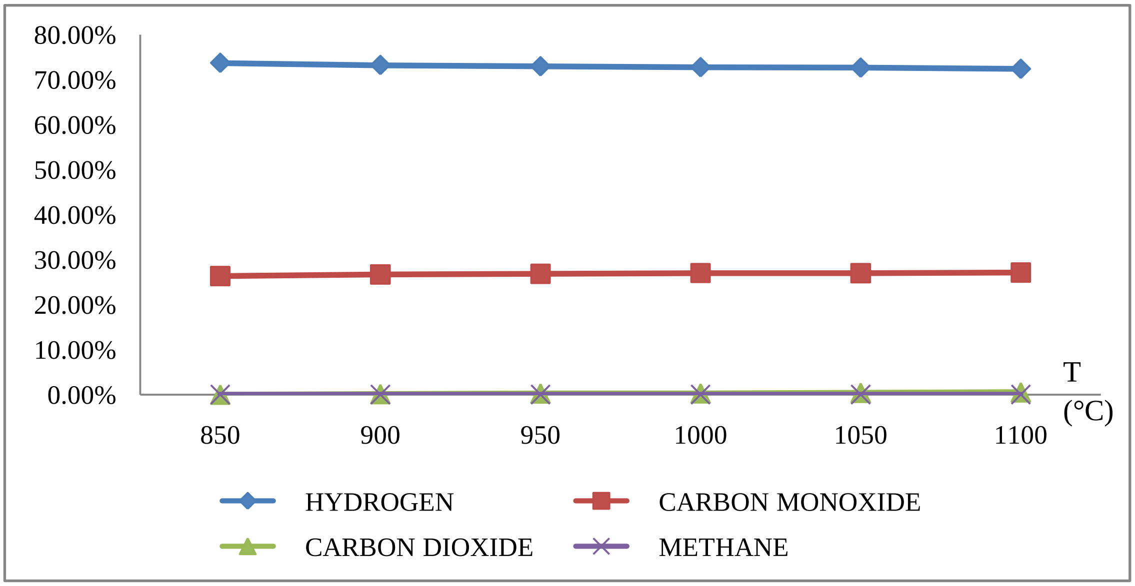


Figure 13: Effect of temperature on product gas composition (Case 2)

From the above figure, we can see that the effect of temperature ranging from 850°C to 1100°C on the product gas composition at a specific condition of steam-to-biomass ratio of 2.4 and pressure at 1 atmospheric. The plot shows production of hydrogen is almost constant throughout the temperature range studied. However production of other product gas like carbon dioxide shows increases trend, but carbon monoxide production decreases over an increased temperature.

Although there is not much difference on overall trends of the plot, consistent amount of gases is observed at 850^{o}C and onwards. This is due to the amount of carbon monoxide and carbon dioxide is almost stable, hence the improvement can be done at this point via manipulating other effects such as to increase steam-to-biomass ratio to convert more carbon monoxide to carbon dioxide and hydrogen, and also to increase adsorbent-to-biomass ratio to capture more carbon dioxide to drive the overall reaction scheme to produce more hydrogen. Mahishi et al. [10] also reported that the optimum operating temperature of his system is at 1030 K which is equal to 857^{o}C.

4.3 CASE 3: Biomass was represented by $C_{3.4}H_{4.1}O_{3.3}$ at atmospheric pressure gasification.

In result and discussion of case 3, it will mainly discuss about the findings from the simulation. In this section until the time being, all simulation results are based on an assumption of EFB is represented by $C_{3.4}H_{4.1}O_{3.3}$ only and the whole system is to be in atmospheric pressure.

As from chapter 2 not much literature review has been done for this part due to time constraint as this task is a side task (beside the main task – high pressure gasification). However, most of the research team too starts with the flowsheeting work by dividing the plant into three sections namely feedstock processing, gasifier or gasification reactor, and last part is purification before Hydrogen is being produced. In order to start the simulation, reactions must be known and finalized before proceed to kinetic researched.

4.3.1 Reactions in Integrated gasification unit

Before the gasification unit needs to be operated, we must first know the reaction in the gasification unit. From Chapter 1 in this report, we understand that there are six reactions to be researched. As from the table below, the entire reaction scheme has been changed due to the balance equation when $C_{3.4}H_{4.1}O_{3.3}$ is being applied into the equation.

Table 7: Reactions and its enthalpy (Case 3)

Reaction name	Reaction
Carbon Gasification	$C_{3.4}H_{4.1}O_{3.3} + 0.1H_2O \rightarrow 3.4CO + 2.15H_2$
Methanation	$C_{3.4}H_{4.1}O_{3.3} + 8.05H_2 \rightarrow 3.4CH_4 + 3.3H_2O$
Methane Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$
Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$
Boudouard	$C_{3.4}H_{4.1}O_{3.3} + CO_2 \rightarrow 4.4CO + 0.9H_2O + 1.15H_2$
CO_2 Removal	$CO_2 + CaO \rightarrow CaCO_3$

4.3.2 Kinetic Research

As shown in table 8, we see that the kinetics of Empty Fruit Bunch for atmospheric pressure has finally been found. For gasification, the kinetic were support by Corella J et al. [26], Gonzalez et al. [27], and C. Fushimi et al. [38]. Next, methanation and bouduard kinetics were found the kinetic in a paper by Marcio L. de Souza-Santos [39] and we applied it into our system. As usual methane reforming were very widely being researched. With this, we have four authors supporting a single kinetic which are Corella J. et al. [26], Therien N. et al. [31], Liu H. et al. [32], and Fletcher D. F. et al. [33] while Corella J. er al., [26] Gonzalez et al., [27] Xu J. et al., [34] and Simell P. A. et al. [35] agreed with the same kinetic for the water gas shift reaction. Carbonation was supported by Ping S. et al. [40].

Table 8: Kinetics research on reactions for gasification (Case 3)

Reaction	Kinetics	Reference
Gasification	2.0×10^{5} exp (-6000/T)	[26] , [27] , [38]
Methanation	2.345×10^{-11} exp (-13670/T)	[39]
Bouduard	$1.19\text{x}10^{-3}$ exp (-16840/T)	[39]
Methane reforming	$3\text{x}10^{5}$ exp (-15000/T)	[26] , [31] , [32] , [33]
WGS	10^{6} exp (-6370/T)	[26] , [27] , [34] , [35]
Carbonation	1.67×10^{-3} exp (-29/T)	[40]

4.3.3 Process Assumptions

Assumptions made regarding the gasification of biomass are listed below:

1. Biomass is Empty Fruit Bunch, $C_{3.4}H_{4.1}O_{3.3}$.
2. Gasification unit is assumed to be in adiabatic condition.
3. Carbonation is assumed to be forward reaction only.
4. Ash will not participate in the reaction (assume to be inert).

4.3.4 Process Description

All process descriptions are as of above in section 4.1.4. Please refer above for accuracy of each analysis performed. However, in this case, we will mainly focus on atmospheric pressure and assuming Empty Fruit Bunch as $C_{3.4}H_{4.1}O_{3.3}$ only.

4.3.5 Steam to Biomass ratio

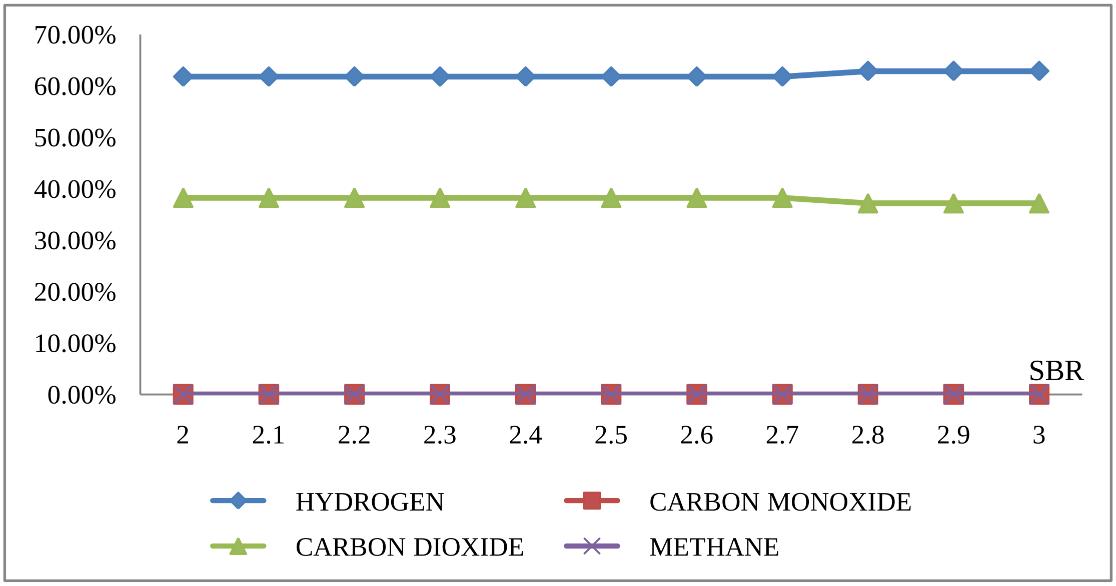


Figure 14: Effect of Steam to Biomass ratio on product gas composition (case 3)

From the above figure, we can see that the effect of steam to biomass ranging from 2 to 3 on the product gas composition at a specific condition of temperature of 850°C and pressure at 1 atmospheric. The plot shows production of hydrogen is almost constant throughout the temperature range studied. However, hydrogen gas was reported to be a little increase after ratio reaches 2.7. On the other hand production of other product gas like carbon dioxide, carbon monoxide, and methane were constant throughout the range of investigation.

Although there is not much difference on overall trends of the plot, consistent amount of gases is observed towards the trend. This is due to the kinetic used in the system poses slow reaction except for gasification and water gas shift reactions. Hence there are improvements to be done at this point via manipulating other effects such as to increase temperature to convert more other components into hydrogen.

4.3.6 Pressure

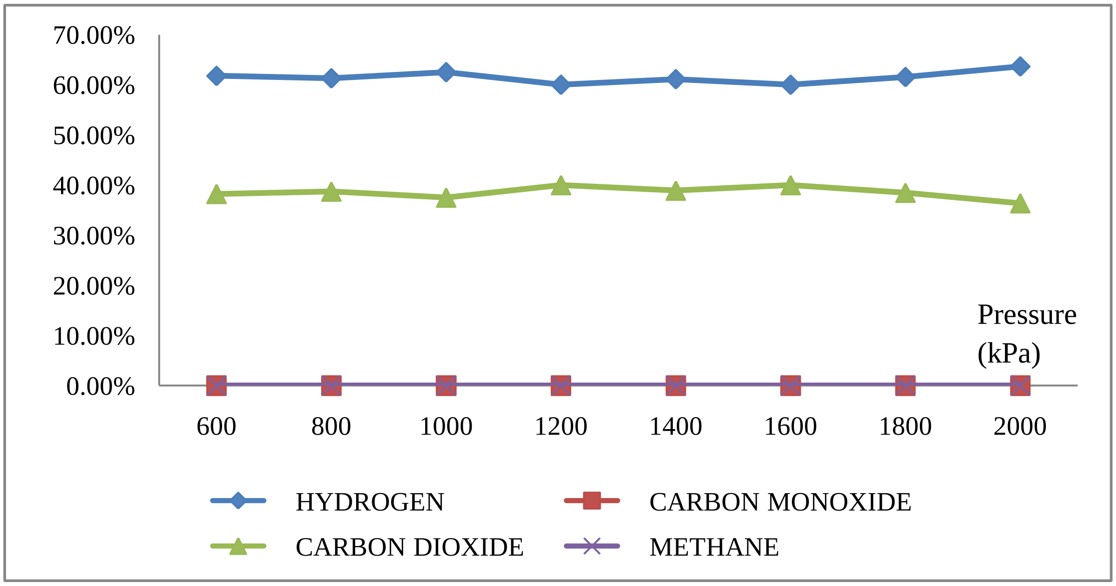


Figure 15: Effect of pressure on product gas composition (Case 3)

From the above figure, we can see that the effect of pressure ranging from 600kPa to 2000kPa on the product gas composition at a specific condition of steam-to-biomass ratio of 2.0 and temperature at 850°C. The plot shows production of hydrogen is almost constant throughout the pressure range studied with a little fluctuation due to the sensitivity of reactions. However production of other product gas like methane and carbon monoxide production was constant zero with increased pressure. Carbon dioxide production maintains fluctuating with the fluctuation of hydrogen production.

Although there is not much difference on overall trends of the plot, consistent amount of gases is observed. This is due to the amount of carbon monoxide and methane is almost stable, hence the improvement can be done at this point via manipulating other effects such as to increase steam-to-biomass ratio to convert more hydrogen production, and also to increase adsorbent-to-biomass ratio to capture more carbon dioxide to drive the overall reaction scheme to produce more hydrogen.

4.3.7 Temperature

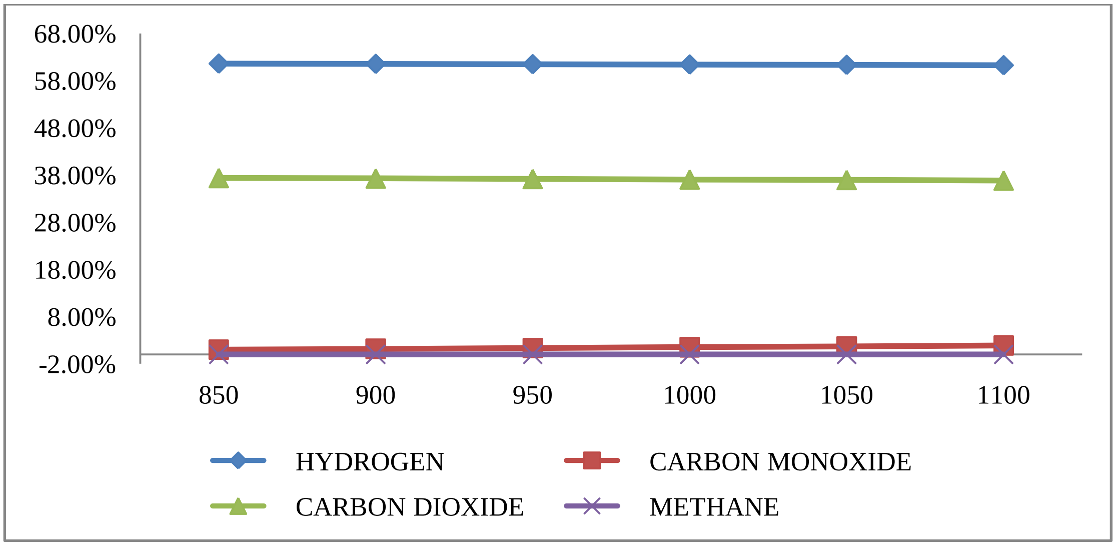


Figure 16: Effect of temperature on product gas composition (Case 3)

From the above figure, we can see that the effect of temperature ranging from 850°C to 1100°C on the product gas composition at a specific condition of steam-to-biomass ratio of 2 and pressure at 1 atmospheric. The plot shows production of hydrogen is almost constant throughout the temperature range studied. However production of other product gas like carbon monoxide shows increases trend, but carbon monoxide and methane production shows constant rate of production over an increased temperature.

Although there is not much difference on overall trends of the plot, consistent amount of gases is observed at 850^{o}C and onwards. This is due to the amount of carbon monoxide and carbon dioxide is almost stable, hence the improvement can be done at this point via manipulating other effects such as to increase steam-to-biomass ratio to convert more carbon monoxide to carbon dioxide and hydrogen, and also to increase adsorbent-to-biomass ratio to capture more carbon dioxide to drive the overall reaction scheme to produce more hydrogen. Mahishi et al. [10] also reported that the optimum operating temperature of his system is at 1030 K which is equal to 857^{o}C.

CHAPTER 5
ECONOMIC EVALUATION

Economic of the high pressure gasification of Empty Fruit Bunch system was being determined and evaluated according to the process flow sheet mentioned in the previous chapter. However, in this stage, we will only analyze for economic potential level one. Data gathered for price of all the raw material and production costs are as of below:

Table 9: Raw material cost

Material	Price (USD / ton)	Source
Steam	10.40	[25] & MOX (2009)
Empty Fruit Bunch	40.00	[24]
Calcium Oxide Catalyst	2400.00	[25]

Table 10: Product cost

Material	Price (USD / ton)	Source
Hydrogen	3300	Estimation

Assumptions to determine the economic potential level one of the high pressure gasification system are as of below:

(a) All production rates are as of average or mid range according to the table above.
(b) Plant operate only 330days per year, 24hours per day.

CASE1: High pressure gasification with assumption biomass is carbon.

Operating conditions to calculate the economics feasibilities of high pressure gasification of Empty Fruit Bunch into Hydrogen are as of below:

Table 11: Operating parameters used to calculate economic potential level one (Case 1)

Parameters	Variables	Unit
Temperature	1400	Degree C
Pressure	600	kPa
Steam to Biomass ratio	2.45	-

From the above operating condition we find that the production and the reactants given in table 16 below:

Table 12: Amount of reactants and products at the selected operating parameters (Case 1)

Material	Amount (kg/hr)	Amount (ton/yr)
Steam	2.45	19.404
Empty Fruit Bunch	1	7.92
Calcium Oxide	0.01	0.0792
Hydrogen production	0.18	1.4256

In order to have the system economically viable, revenue of the system must be higher than the cost. Main reason is to gain profit out of the process while second reason is to recover back the capital cost that has been imposed into the manufacturing of equipments and man power. However, since we are focusing on economic potential level one only, we will only consider the cost of all inlet and outlet material.

Economic potential level one was being calculated as of below:

Economic Potential Level ONE = Revenue – Raw cost material

In order to have profit out of this process flow, we must obey to the inequalities as of below:

Revenue – Cost ≥ 0 (Revenue – cost must not equals to zero or less than zero)
Revenue ≥ Cost (Revenue must more than cost)
[USD (Hydrogen)] - [USD (Steam + Calcium Oxide + EFB)] ≥ 0

[(1.4256 ton / yr x USD 3300 / ton)] – [(0.0792 ton / yr x USD 2400 / ton) + (7.92 ton / yr x USD 40 / ton) + (19.404 ton / yr x USD 10.40 / ton)]

= USD 4704.48 / yr – (USD 190.08 / yr + USD 316.8 / yr + USD 201.8016 / yr)
= USD 3995.80 / yr (net profit)

Revenue is higher than Cost by USD 3995.80 per year.

With this amount of revenue per year, we will finally consider that, this process is applicable to the real industrial. This profit would be multiply if the real case involved high amount of feed and product.

CASE 2: Atmospheric pressure gasification with assumption biomass is carbon.

Operating conditions to calculate the economics feasibilities of high pressure gasification of Empty Fruit Bunch into Hydrogen are as of below:

Table 13: Operating parameters used to calculate economic potential level one (Case 2)

Parameters	Variables	Unit
Temperature	850	Degree C
Pressure	101.325	kPa
Steam to Biomass ratio	2.0	-

From the above operating condition we find that the production and the reactants given in table 16 below:

Table 14: Amount of reactants and products at the selected operating parameters (Case 2)

Material	Amount (kg/hr)	Amount (ton/yr)
Steam	0.24	1.9008
Empty Fruit Bunch	0.12	0.9504
Calcium Oxide	0.05	0.396
Hydrogen production	0.06	0.4752

In order to have the system economically viable, revenue of the system must be higher than the cost. Main reason is to gain profit out of the process while second reason is to recover back the capital cost that has been imposed into the manufacturing of equipments and man power. However, since we are focusing on economic potential level one only, we will only consider the cost of all inlet and outlet material.

Economic potential level one was being calculated as of below:

Economic Potential Level ONE = Revenue – Raw cost material

In order to have profit out of this process flow, we must obey to the inequalities as of below:

Revenue – Cost ≥ 0 (Revenue – cost must not equals to zero or less than zero)

Revenue $\geq$ Cost (Revenue must more than cost)

[USD (Hydrogen)] - [USD (Steam + Calcium Oxide + EFB)] ≥ 0

[(0.4752 ton / yr x USD 3300 / ton)] – [(0.396 ton / yr x USD 2400 / ton) + (0.9504 ton / yr x USD 40 / ton) + (1.9008 ton / yr x USD 10.40 / ton)]

= USD 1568.16 / yr – (USD 950.40 / yr + USD 38.016 / yr + USD 19.7683 / yr)

= USD 559.98 / yr (net profit)

Revenue is higher than Cost by USD 559.98 per year.

With this amount of revenue per year, we will finally consider that, this process is applicable to the real industrial. This profit would be multiply if the real case involved high amount of feed and product.

CASE 3: Atmospheric pressure gasification with assumption biomass as $C_{3.4}H_{4.1}O_{3.3}$.

Operating conditions to calculate the economics feasibilities of high pressure gasification of Empty Fruit Bunch into Hydrogen are as of below:

Table 15: Operating parameters used to calculate economic potential level one (Case 3)

Parameters	Variables	Unit
Temperature	850	Degree C
Pressure	101.325	kPa
Steam to Biomass ratio	2.0	-

From the above operating condition we find that the production and the reactants given in table 16 below:

Table 16: Amount of reactants and products at the selected operating parameters (Case 3)

Material	Amount (kg/hr)	Amount (ton/yr)
Steam	0.24	1.9008
Empty Fruit Bunch	0.12	0.9504
Calcium Oxide	0.01	0.0792
Hydrogen production	0.06	0.4752

In order to have the system economically viable, revenue of the system must be higher than the cost. Main reason is to gain profit out of the process while second reason is to recover back the capital cost that has been imposed into the manufacturing of equipments and man power. However, since we are focusing on economic potential level one only, we will only consider the cost of all inlet and outlet material.

Economic potential level one was being calculated as of below:

Economic potential level one = Revenue – Raw cost material

In order to have profit out of this process flow, we must obey to the inequalities as of below:

Revenue – Cost ≥ 0 (Revenue – cost must not equals to zero or less than zero)

Revenue ≥ Cost (Revenue must more than cost)

[USD (Hydrogen)] - [USD (Steam + Calcium Oxide + EFB)] ≥ 0

[(0.4752 ton / yr x USD 3300 / ton)] – [(0.0792 ton / yr x USD 2400 / ton) + (0.9504 ton / yr x USD 40 / ton) + (1.9008 ton / yr x USD 10.40 / ton)]

= USD 1568.16 / yr – (USD 190.08 / yr + USD 38.016 / yr + USD 19.7683 / yr)

= USD 1320.30 / yr (net profit)

Revenue is higher than Cost by USD 1320.30 per year.

With this amount of revenue per year, we will finally consider that, this process is applicable to the real industrial. This profit would be multiply if the real case involved high amount of feed and product.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

This project has completed its original set objective and target successfully which feasible foute to produce Hydrogen from Empty Fruit Bunch at high pressure has been investigated. Integrated gasification is the efficient gasification unit to improve the productivity of hydrogen. Second objective has also been accomplished where feasible route with operating conditions has been investigated. Besides that, Flowsheet has been restructure and developed to suit the integrated version where pressurized catalytic gasification unit in iCON. After that, identification of the optimum operating conditions has been carried out and the result is, higher temperature, higher steam to biomass ratio and higher pressure, all the system will increase hydrogen yield. Economics feasibility has also been identified in term of economic potential level one only.

With this, further research and analysis has to be carried out in order to ensure the researched statements are correct in the sense of application in Malaysia. Besides that, the kinetic of catalyst are to be further studied as most of the researchers do not include the studies on Empty Fruit Bunch and combination of catalytic and pressurized system. This has the chance of excluding the high pressure system kinetics where empty fruit bunch were employed instead of assuming empty fruit bunch as carbon at this moment. Next, economic wise, one must investigate the cost of building the plant and the payback period as building a high pressure plant might be costly. All and all, the development of integrated pressurized catalytic fluidized gasification process is hopefully to be greatly useful for the future economic and environment.

REFERENCES

[1] P. McKendry, *Energy Production from biomass (Part 3): gasification* technologies, Review paper, Applied Environmental Research Centre Ltd, UK

[2] S. Babu, *Biomass Gasification for Hydrogen Production – Process Description and research Needs, Thermal Gasification of Biomass*, IEA Bionergy Agreement, Gas Technology Institute, Dublin, Ireland

[3] L. G. Sheng and T.W. Kwang, *1MWe Biomass Modular Power Plant*, China EnerSave Ltd, China, April 2004

[4] A. Hussain, F. N. Ani, A. N. Darus, H. Mokhtar, S. Azam, A. Mustafa, *Thermodynamical Behaviour of Empty Fruit Bunches and oil palm shell waste in a Circulating Fluidized Bed Combustor (CFBC)*, Journal of Oil Palm Research Vol. 18 June 2006 page. 210 – 218.

[5] W. Wang, G. Olofsson, *Reduction of Ammonia and Tar in Pressurized Biomass,* Lund University, Sweeden

[6] *An overview of Biomass Gasification,* www.nrel.gov/**biomass**/pdfs/**overview_biomass_gasification**.pdf

[7] TSS Consultants, *Gridley Ethanol Demonstration Project Utilizing Biomass Gasification Technology: Pilot Plant Gasifier and Syngas Conversion Testing August 2002—June 2004*, National Renewable Energy Laboratory, Gridley, California.

[8] S. P. Babu, *OBSERVATIONS ON THE CURRENT STATUS OF BIOMASS GASIFICATION*, 17 March 2005.

[9] K. Maniatis, European Commission, *Progress in Biomass Gasification: An Overview*, Belgium

[10] C. D. Blasi, *KINETIC MODELING OF BIOMASS GASIFICATION AND COMBUSTION*

[11] K. Matsuoka, *FACTORS AFFECTING STEAM GASIFICATION RATE OF LOW RANK COAL CHAR IN A PRESSURIZED FLUIDIZED BED, 2009*

[12] J. Fermoso, B. Arias, M.G. Plaza, C. Pevida, F. Rubiera, J.J. Pis, F. García-Peña, P. Casero, *High-pressure co-gasification of coal with Biomass and Petroleum Coke,* Belgium, 2009

[13] M. R. Mahishi, Goswami D. Y. "Thermodynamics optimization of biomass gasifier for hydrogen production*", International Journal of Hydrogen Energy,* Vol 32, p. 3831-3840, 2007.

[14] F. S. Lau, *Techno-Economic Analysis of Hydrogen Production by Gasification of Biomass,* Gas Technology Institute, 2002

[15] Yong., Potential of hydrogen from oil palm biomass as a source of renewable energy worldwide, Energy Policy, 35, 2007

[16] L. Shen, Y. Gao, J. Xiao, *Simulation of Hydrogen production from biomass gasification in interconnected fluidized beds,* Southeast University, Nanjing, China, 2007

[17] S. Lin, M. Harada, Y. Suzuki, H. Hatano, *Hydrogen production from coal by separating carbon dioxide during gasification,* Onogawa, Tsukuba, Japan

[18] D. K. Lee, I. H. Baek, W. L. Yoon, *Modeling and simulation for the methane steam reforming enhanced by in situ* CO_2 *removal utilizing the CaO carbonation for* H_2 *production,* Republic of Korea, 2003

[19] V. Biba, J. Macak, E. Klose and J. Malech, *Mathematical Model for the Gasification of Coal Under Pressure,* Prague, Czechoslovakla, and Freiberg, 2002

[20] P. Raman, W. P. Walawender, L. T. Fan, and C. C. Chang, *Mathematical Model for the Fluid-Bed Gasification of Biomass Materials. Application to Feedlot Manure,* Department of Chemical Engineering, Kansas State University, Manhattan, Kansas.

[21] P. Lv, X. KONG, C. WU, Z. YUAN, L. MA, J. CHANG, *Modeling and simulation of biomass air-steam gasification in a fluidized bed,* Guangzou Institure of Energy Conversion, Guangdong, Guangzhou, China.

[22] N. H. Florin, A. T. Harris, *Enhanced hydrogen production from biomass with in situ carbon dioxide capture using calcium oxide sorbents,* University of Sydney, NSW, Australia, 2006

[23] T. Hanaoka, T. Yoshida, S. Fujimoto, K. Kamei, M. Harada, Y. Suzuki, H. Hanato, S.Yokoyama, T. Minowa, *Hydrogen production from woody biomass by steam gasification using a* CO_2 *sorbent,* Japan, 2004

[24] Hydrogen Economy, National Academic Press, 2004

[25] Peters et al. (2003), Renewable Energy, Vol 33, 2008, pp 1874-1879

[26] Corella, J., and Sanz, A., Modeling circulating fluidized bed biomass gasifiers. A-pseudo-rigorous model for stationary state, Fuel Processing Technology, 86, p. 1021 – 1053, 2005.

[27] Gonzalez, S.J., Advances in biomass gasification in fluidized bed, PhD thesis, University of Saragossa (Dept. Of Chemical Engineering), 1988.Unpublished.

[28] Choi, Y.C., Li, X.Y., Park, T.J., Kim, J.H., and Lee, J.G., Numerical study on the coal gasification characteristics in an entrained flow coal gasifier, Fuel, vol. 80, p. 2193-2201, 2001.

[29] Govin, R., and Shah, J., Modeling and simulation of an entrained flow coal gasifier, AIChE Journal, Vol. 30,p. 79, 1984.

[30] Brown, B.W., Smoot, L.D., Smith, P.J., and Hedman, P.O., Measurement and prediction of entrained flow gasification process, AIChE Journal, Vol. 34, p. 435, 1988.

[31] Therien, N., Marchand, P., Chamberland, A., and Gravel, G., Computer modeling and simulation of biomass fluidized bed gasifier, Proceeding of the XVIII Congress: The Use of Computer in Chemical Engineering-CEF87, 26-30 April, Gianardi Naxos,Italy, p. 187-192, 1987.

[32] Liu, H., and Gibbs, B.M., Modeling NH3 and HCN emissions from biomass circulating fluidizied biomass gasifiers, Fuel, vol. 82. p.1591 - 1604, 2003.

[33] Fletcher, D.F., Haynes,D.S., Christo, F.C., and Joseph, S.D., A CFD based combustion model of an entrained flow biomass gasifier, Applied Mathematics Modeling, Vol. 24, p. 165-182, 2000.

[34] Xu, J., and Froment, G.J., Methane steam reforming, methanation and water gas shift: 1. intrinsic kinetics, AIChE Journal, vol. 35, p. 88-96, 1989.

[35] Simell, P.A., Hirvensalo, E.K., Smolander, S.T., and Krause,A.O., Steam reforming of gasification gas tar over dolomite with benzene as a model compound, Industrial and Engineering Chemistry Research, vol.38, p. 1250, 1999.

[36] Irfan, A., and Dogu, G., Cacination kinetics of high purity limestones, Chemical Engineering Journal, vol.83, p. 131-137, 2001.

[37] Milne, C.R., Silciox, G.R., Pershing, D.W., Kirchgesner, D.A., Calculation and sintering models for applications of high temperature short time sulfaction of calcium based sorbent, Ind Eng. Chem. Res., vol. 29,p. 139-152, 1990.

[38] C. Fushimi, K. Araki, Y. Yamaguchi and A. Tsutsumi "Effect of heating rate on steam gasification of biomass: 1. Reactivity of char", *Industrial and Engineering Chemistry Research* 42 (2003) 3922-3928

[39] Marcio L. de Souza-Santos " Solid Fuels Combustion and gasification: Modeling, Simulation and Equipment Operation" Marcel Dekker, New York, USA (2004) pp. 146-159

[40] Ping Sun, John R. Grace, Jim Lim and Edward Anthony "Determination of intrinsic rate constants of the CaO-CO2 reaction", *Chemical Engineering Science* 63 (2008) 47-56

[41] Gao N., Li A., Quan C., A Novel reforming method for hydrogen production from biomass steam gasification, Bioresource Technology, Vol. 100, p. 4271-4277, 2009.