



UNIVERSITY OF INDONESIA

**CHARACTERISTICS OF LOW TEMPERATURE GASIFICATION OF
VICTORIAN BROWN COAL**

THESIS

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BACHELOR PROGRAMME
DEPOK
JUNE 2012**



UNIVERSITY OF INDONESIA

**CHARACTERISTICS OF LOW TEMPERATURE GASIFICATION OF VICTORIAN
BROWN COAL**

TITLE PAGE

THESIS

Prepared as one of the requirement to obtain the title

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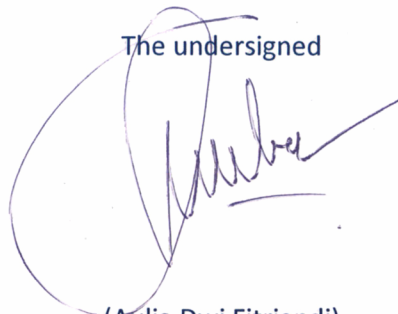
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PREFACE

Writer would like to give praise and gratitude to Allah SWT for His bless, grace and guidance so this thesis could be done. The paper which entitled as “ **CHARACTERISTICS OF LOW TEMPERATURE GASIFICATION OF VICTORIAN BROWN COAL**” is created as a partial fulfillment of Sarjana Teknik title and the task of thesis course.

In the preparation of this thesis, authors get a lot of help feom many people. In particular author wish to thank Dr. Ir. Asep Handaya Saputra M.Eng and Dr. Lian Zhang as the authors supervisors whose provide valuable guidance, direction and feed back so this task could be accomplished.

Authors would also like to say thank you and sincere gratitude to:

- Author’s parents and family, for support, love and care
- Board of Chemical Engineering Lecturers at University of Indonesia and Monash University
- Bavadra W Mojilip as my project partner and Ms. Juan Chen for her help during the experiment
- All friends from chemical engineering especially the internatonal program who always gives support and good times when things seems bad

Writers is fully realize that this work is far from perfect thus, criticism and suggestion are welcome to improve this paper further. Hopefully this thesis can give information and benefit to whom reading it.

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ABSTRACT

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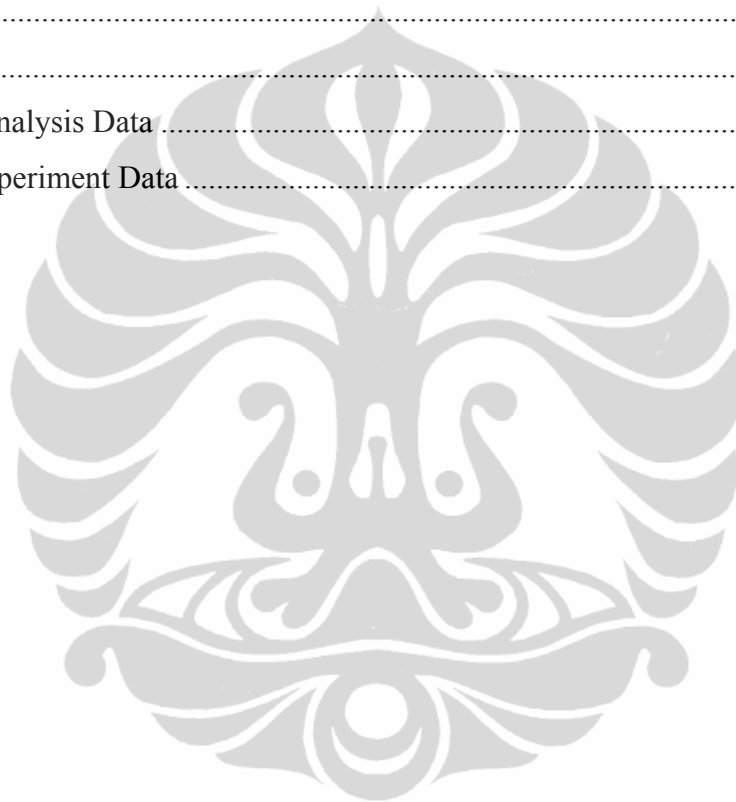
The conventional method of generating energy is by means of combustion puts significant pressure on the environment. Therefore the study of gasification is needed. Low temperature gasification produces synthetic gas as a fuel or material to produce chemicals in industry. This study investigated the gasification characteristics of Victorian brown in terms of reaction competition and structural changes happen. It was found that as the concentration of oxygen reaches 5% and 6 second residence time, char yield goes to as low as 45 % to 25 % , the char yield decreases, which indicates more synthetic gas was produced in the reaction. The structural changes of char during gasification were also observed, results shows the reaction mechanism of char as it goes through gasification. This is illustrated by the BET surface area, pore volume and also the pore size. In CO₂ dominated reaction, the surface area goes as high as 240 m²/g to 180 m²/g due to char fragmentation and promptly decrease to around 170 m²/g, while in O₂ reaction the surface area dropped to around 160 m²/g. SEM analysis shows considerable increase in the frequency of char particles which diameter smaller than 120 microns (from 0.27 to 0.36 for particle smaller than 100 microns and from 0.28 to 0.35 for particle at 100 to 120 microns). While there is a noticeable decrease in the frequency of larger particle (0.26 to 0.19 for 120 to 140 microns, 0.09 to 0.06 for 140 to 160 microns and 0.1 to 0.03 for larger than 160 microns)

Keywords : Gasification, Victorian brown coal, char yield

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Chapter 1

INTRODUCTION

1.1 Background

Brown coal has been the important power generation source of Victoria State due to its abundant in reserve and low production cost. Currently 85% of electricity used in Victoria are produced by from steam turbine power plant which used heat released from brown coal combustion to generate steam. Coal combustion has low energy efficiency due to high moisture content of the Brown coal and most importantly this method of energy generation is not environmentally friendly since the combustion of Victorian brown coal liberate a significant amount of carbon dioxide and another environmental hazardous material such as SO_x and NO_x, thus it is necessary to develop a cleaner technology to utilize the brown coal as a source of energy to fulfil electricity demand while conserving the environment. Gasification is one of the promising methods for brown coal utilization in the carbon-constrained future. Gasification produce less amount of carbon dioxide, accommodate carbon capture and significantly reduce the amount of SO_x and NO_x emission compared to the currently utilized combustion method. In addition the product of the gasification which is syngas can be used as the source of energy or precursor to other chemical product, in an advanced system the syngas power generation will has higher overall efficiency than the combustion power cycle. However with the current technology and understanding, gasification process is less favourable due to its relatively slow reaction rate compared to the combustion process therefore considered to be rate controlling step and the complexity of syngas utilization, thus a lot of amount work and research must be done in this field of study in order to obtain a better understanding of this process and improve its efficiency.

This study has an aim to investigate the characteristics of low temperature gasification brown coal char. This aim broke down into several objectives which are to develop a relationship between the residence time and gasifying gas

composition to reaction rate and completion which are represented by char yield percentage. Secondly, the change in the structural properties of the char will be investigated to seek an explanation about the gasification reaction mechanism. Finally, the results of this study are hoped to give a contribution to further study of the utilization of brown coal through gasification, thus sustainable development for the future could be achieved.

1.2 Problem Statement

Gasification is a promising technology, which exploits low-rank coal such as brown coal because of the high gasification reactivity. Hence gasification provides a promising outlook as a clean and cheap way to generate energy by utilizing brown coal. However, further research is imperative to progress our understanding of coal and its properties during gasification to increase its efficiency and establish its usage .

Extensive amount of research has been done on this field. However, the research are mostly concern on the gasification process itself and less attention was given on the feedstock of gasification which is coal. It is trivial that characteristic of the feedstock coal greatly affect the performance of gasification process especially the structural properties of the coal such as size and porosity, thus further study on this matter is imperative as to utilize the gasification to its most efficient extent.

1.3 Objectives

This study is aimed to:

- Establish a correlation between reaction time and the composition of gasifying gas in terms of oxygen concentration to the reaction completion which represented by char yield.
- Investigate changes in structural properties of char (porosity, surface area and size distribution) along the course of gasification reaction as to understand the reaction behaviour of solid char with gasifying gas (CO₂ and O₂).

1.4 Scope

This study will be bounded on the Victorian, Loy Yang brown coal and the investigation of gasification rate by using a pilot scale gasification drop tube reactor in 3 different gasifying gas compositions within 3 different retention times. The experiments only consider the features and behaviour of the coal gasification with mixture of Carbon Dioxide and Oxygen gas as gasifying gas. The coal used on this experiment is constrict only to 1 type of coal which is the high ash Victorian brown coal char with 103 – 153 nm particle size and also the reaction temperature is maintained to be constant between 800 to 1000 centigrade while the reaction pressure is not controlled . Therefore the study will be investigated the effect of the residence time and the composition of the gasifying gas composition to the reaction completion, while the effect of temperature and pressure are not investigated in this study.

The measurements of reaction completion and reaction rate are represented by char yield percentage and there are two methods used to determine the structural properties of the char, which are the surface area analysis and the Particle size and diameter analysis using SEM.

Chapter 2

LITERATURE REVIEW

2.1 Brown Coal in Victoria

Brown coal is found in three tertiary basins across the state of Victoria, there are Murray basin, the Otway Basin and the Gippsland basin. Gippsland basin is the largest in terms of brown coal reserve which is estimated to be 65,00 Mt and followed by the Murray basin and Otway basin which have 19,600 Mt and 15,500 Mt brown coal in reserves respectively ^[7] With over 100,000 Mt of high quality brown coal reserves at hand, Victorian brown coal has become the main source of energy and had a long history of its utilization to meet the energy demand of Victoria State and Australia. Currently, the electricity in the state of Victoria is largely fuelled by brown coal, with not less than 85 % of it are generated by utilizing lignite or brown coal, therefore it can be concluded that the brown coal utilization is one of the driving force and foundation of steady economic growth in Victoria ^[6]

The main utilization of Victorian brown coal has been the electricity generation through direct combustion in Yallourn power station in La Trobe valley, while a minor amount of brown coal is also serve for another purpose. The Victorian brown coal or lignite has a unique characteristic in comparison with other fuel types and considered as a low rank coal. These unique characteristic includes the structural and chemical features which differentiates it from other fuel sources, Brown coal has a well distributed alkali and alkaline earth metal (AAEM) species and these metal form either carboxylates or NaCl dissolved in its high moisture content ^[13] This unique characteristic contributes to its reaction behaviour during gasification which favours the reaction in certain ways thus the gasification in lower temperature is possible ^[16] this phenomenon will be discussed further in later part of this report. However, the lignite's moisture content is higher than its other counterparts, which translate to lower combustion efficiency.

2.1 Features of Victorian Brown Coal

The efficient use of the Victorian brown coal while keeping the environmental aspect of its utilization in check depends on the understanding of the structural features and properties of the Victorian brown coal. The brown coal which deposited in the Latrobe Valley, Victoria are categorized as low rank, tertiary age coal and this type of coal has a unique characteristic in almost all of its aspect compared to other solid fuels such as biomass, bituminous coal and anthracite ^[7]. This part of the report will outline those characteristics, which made Victorian brown coal suitable as environmentally friendly source of energy through gasification method.

Brown coal has high oxygen content like any other low rank coal, the oxygen content ranges from 22 to 27 wt %. The oxygen exists within the coal structures in many chemical function groups such as the acidic functional groups ^[10]. The acidic functional groups which consist of carboxyl and phenol groups are carry metallic compound in its molecular structure, since brown coal has high amount of oxygen, these acidic groups are dispersed well in the structure of the coal and thus made the metallic compounds to be dispersed as well ^[17]. Recent studies shows that the presences of this metallic compounds are catalyse the gasification reaction to some extent, therefore due to its well distributed particles in brown coal, the presences of oxygen which helps to distribute the metallic compounds are an advantage in the brown coal utilization through combustion ^[12]

Next, The Victorian brown coal has high content of AAEM content dispersed in the coal structural matrix. AAEM Stands for Alkaline and Alkaline Earth Metal such as Na, Mg and Ca. These species are usually presence in two forms in the brown coal structures, namely cations associated with carboxyl group and soluble salts which associated with moisture content ^[17]. The AAEM compounds behave differently from other mineral species in brown coal, it has significant impacts in all of the known utilization method of brown coal, as an example in the direct combustion of brown coal, AAEM is believed to be the source of ash related problem such as fouling and slugging ^[4] while in the power generation using gasification method, AAEM presence could cause erosion and corrossions problem

of the process component ^[18]. Although it has some of disadvantages, the AAEM compounds can act as an excellent catalyst for char gasification, particularly that these compounds are well dispersed in the brown coal structures thus boosting the catalysation process. Therefore an understanding of the mechanism and volatilization of the AAEM is crucial part in the future studies of Victorian brown coal ^[9].

Lastly, the specific characteristic that differs brown coal from other type of coal is its inherent moisture content. Brown coal is known for its high inherent moisture content, it ranges from 50 to 70-wt% when it is freshly mined from the coal seams. Some parts of the moisture content possesses similar properties to normal liquid water thus, this type of moisture content are easy to remove from the brown coal structures ^[14], while some other parts of the moisture content are closely bounded to oxygen functional group in the macromolecular network of brown coal structure, therefore it is really hard to remove by physical mean and it is became inseparable part of the Victorian brown coal ^[18] The water need to be removed before it is being utilized to improve process efficiency and minimize environmental impact.

2.3 Cleaner Energy Potential, Gasification Method

Although the combustion of Victorian brown coal is cheap, abundant in reserve and essential to fulfil the Victoria and Australia electricity needs. This method of energy generation is not environmentally friendly since the combustion of Victorian brown coal liberate a significant amount of carbon dioxide and another environmental hazardous material such as SO_x and NO_x, thus it is necessary to develop a cleaner technology to utilize the brown coal as a source of energy to fulfil electricity demand while conserving the environment. By achieving a scientific understanding on cleaner method to utilize Victorian brown coal will bring the development of energy towards a more sustainable future.



Figure 2.3.1 : Loy Yang, Power Plant, Victoria ^[20]

Gasification is one of the method to utilize brown coal in a much environmental friendly ways. Gasification is a reaction of coal with air, oxygen, steam, carbon dioxide and nitrogen or the mixture of these gases to produce a gaseous product, which can be used as fuel or precursor for synthesizing process of other chemicals ^[2]. In some sense gasification is the same as combustion if there are oxygen presence in the reactants, the main difference between these process is the utilization object, in gasification, the final product which is the syngas is utilized to be used as the source of energy while the combustion utilize the heat generated in the course of the process and the final product of reaction which is the carbon dioxide is considered to be the waste which need to be discharged.

Therefore it can be seen that the gasification process discharge less amount of carbon dioxide waste into the environment, in addition the sulphur and nitrogen content of coal is converted into NH_3 and H_2S in the gasification process, these two compounds is considered to be more environmentally friendly compared to the nitrogen and sulphur related emission in the combustion process which are SO_x and NO_x ^[10]

The gaseous product from gasification is called the synthetic gas or syngas which composed mainly of CO and H_2 , the gas is usually undergo a subsequent process (i.e. water gas shift, liquefaction) before its utilization for energy production. The synthetic gas synthesized from this process has a higher energy output and efficiency when used in an advance system ^[8]

According to the fact mention above, gasification shows a promising value as a cleaner technology to utilize Victorian brown coal. However with the current technology and understanding, gasification process is less favourable due to its relatively slow reaction rate and the complexity of the process compared to the combustion method therefore the gasification method is considered to be not viable for the fulfilling present energy needs, thus a lot of amount work and research has been done in this field of study in order to obtain a better understanding of this process and improve its efficiency^[11]

By altering the gasification rate to be much faster means there will be more syngas produced within the same amount of time thus improve the overall efficiency of brown coal utilization through gasification. There are few factors that would affect the gasification rate. Among them are the structural properties of the char and gasifying gas composition^[11]

The focus and concern of the research revolve around the effect of char structural properties and gasifying gas composition to the rate of gasification, thus the relationship between char reactivity and its structural properties and gasifying agent composition will be build.

2.4 Gasification as Rate Limiting Step

Before gasification could take place, the coal must undergo a process called pyrolysis, otherwise also known as devolatilisation. This process involves the inorganic and hydrocarbon gas undergoing thermal decomposition and leaves the sample as volatile matter. This leaves a solid residue known as char which will be used in the gasification process. Gasification of coal is done by reacting coal with air, oxygen, steam, carbon dioxide, hydrogen or a mixture of these gasses to produce a gaseous emission which can be used as an energy source⁽⁴⁾. Combustion process on the other hand, utilizes direct heat produced from burning coal. For example, directly combusting coal to power a steamed turbine. The gaseous product from gasification is called synthetic gas which can be used to manufacture liquid form fuels. The synthetic gas synthesized from this process has a higher energy output when used in advanced systems. However, the gasification process is the slowest step in the process and therefore considered as

the rate controlling step ⁽¹¹⁾. There are a few factors that would affect the gasification rate. Among them are the concentration of AAEM species and the structural properties of the char ⁽¹¹⁾. Recent studies have also been done to investigate the structural property of the char. Such studies were done by Tunistra and Koenig by building a relationship between the Raman bands with the structural factor which was measured by using X-ray diffraction for polycrystalline graphite. However, Li and Tay mentioned that a quantitative portrayal of the structural properties could not be attained if only D and G bands were considered. They further explained that this is because brown coal chars illustrated a much broader band near D and G bands, further stating that the overlap between these two bands provides rich information with regards to the structural characteristics of brown coal.

2.5 Structural Characteristics and Char Reactivity

The gasification rate is influenced by a few factors which include the dispersion of catalyst, structural properties of the char, and the dispersion of AAEM content in the brown coal. However, this research will focus on the structural properties of char. As stated by Chun-Zhu Li (2007), the structural characteristics of char affects its reactivity in two ways. During the gasification process, the structural properties of the reaction site determine the ease of which the atoms are gasified. Secondly, the effect of the catalyst would be influenced by the char structure. This provides a clear link between the influence of char structure on the reaction rate, both directly (ease of carbon and other atoms to gasify) and indirectly (effect on catalyst dispersion), however, past researchers have failed to take into account of the char size, shape and pore/surface distribution.

2.5 Preceded Experiment Technology and Technique

The structural properties of the char can be studied using a few methods and techniques. Among them is by using Raman spectroscopy which could probe the char structure on a molecular level. The spectral characteristic used is usually the G (graphite) and D (defect) bands ⁽¹²⁾. Another technique is the X-ray diffraction technique or XRD. XRD provides quantitative information about the char structure. However, according to Chun-Zhu Li in 2007, the XRD does not show clear peaks because of the lack of well-oriented carbon structure in the char. In

this study however, the main concern is the morphology of the char so therefore, scanning electron microscope (SEM) and transmission electron microscope (TEM) will be utilized in this study. These techniques provides useful data on the morphology of the char. By complementing this technique with an imaging software (Image-pro), the pore, shape and size distribution can be investigated.



Chapter 3

RESEARCH PLAN

Generally there are four main tasks which need to be done in order to investigate the relation the char structure and gasifying gas composition to the gasification reaction mechanism and rate, they are as followings:

1. Char preparation by pyrolysis
2. Gasification of Char
3. Data analysis
4. Structural Properties of Char Particles analysis

3.1 Materials, Apparatus and Variable

3.1.1 Char Preparation by Pyrolysis and Sieving

Material : Hi ash Loy Yang brown coal, Nitrogen (N₂) Gas

Apparatus : Drop tube furnace, Collecting Apparatus, Sieve, Plastic Container

Next is the preparation of char by coal pyrolysis. The coal, which will be going to analyse for the project, is called hi ash, loy yang brown coal. The coal will be pyrolysed to produce the brown coal char. The pyrolysis process is essentially a devolatilization process of a coal; it removes volatiles from the structure of coal, thus leaves empty space or pores in the coal char. The gases, which were used in the pyrolysis process, are inert nitrogen gas (N₂). Small amount of the char was kept to be analysed later in the structural analysis phase of this project

3.1.2 Char Gasification

Material : Loy Yang brown coal char, Carbon Dioxide (CO₂) gas, Oxygen (O₂) gas

Apparatus : Drop Tube Furnace, Collecting apparatus, Scale, Oven

The gasification stage on this project is considered to be the most important part of this study. To investigate the effect of residence time and gasifying gas

composition to the reaction completion and mechanism, different residence time and gas composition will be employed on this experiment while another operating parameter such as, temperature and pressure are not controlled or held constant. It was decided that the gasifying gas which will be used is the carbon dioxide gas doped with small amount of oxygen and the residence time which are going to be investigated are 2 seconds, 4 seconds and 6 seconds residence time. The experiments will be done in several runs, specifically 3 runs for each conditions, this will be done to minimize the error which possibly occurred in the course of experiment.

This unburnt char will be collected on the bottom of the drop tube furnace. The unburnt char will be investigated to calculate the char yield and to be analysed using SEM and surface area analyser in the structural analysis phase of the project.

3.1.3 Data analysis

Result analysis is comprised of two parts the data analysis and the structural analysis of the char particles

The data analysis phase on this experiment is essentially when all of the char yield data acquired from each run of the experiments was tabulated. The tabulated data will interpret in suitable form, which are in this case the graph form to see the significance of the gasifying gas composition and the residence time to amount of the char yield. The result of the char yield analysis data are predicted to define the behaviour of the gasification reaction in term of the reaction completion, because the char yield represents an indirect measurement of the gasification reaction completion. The analysis will be done mainly using the Microsoft Office excel software to process and compile all of the data.

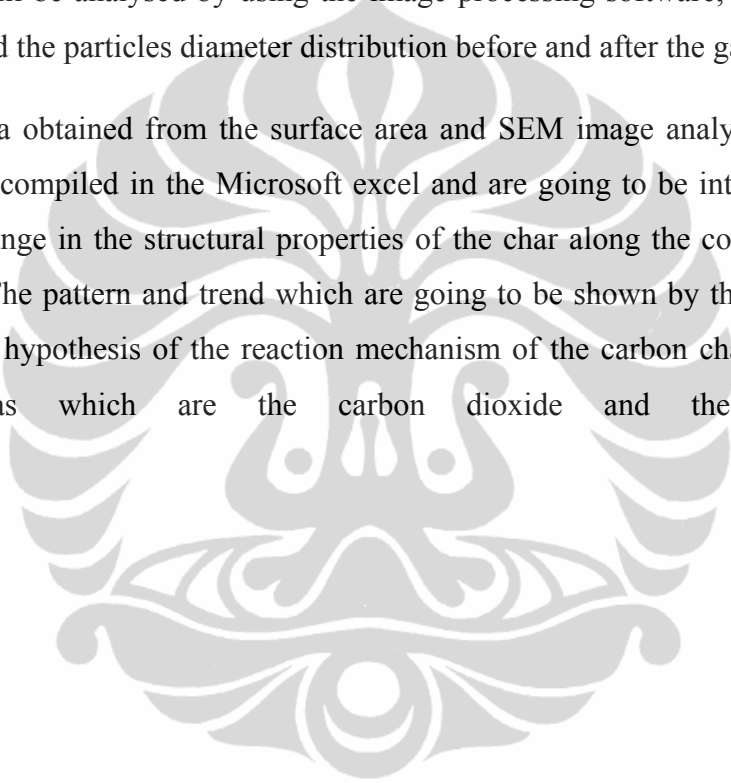
3.1.4 Structural Analysis of the char Particles

The structural analysis of the char particles has an aim to investigate the change in the char structures properties before and after the gasification took place. The char residues which are collected at the end of the experiment will be analysed using

these two followings method, the surface area analysis and SEM image analysis method.

The surface area method employs BET method to calculate theoretical surface area and pore volume of the char particles. This method was done by using the surface area analyser the ASAP 2010 and carbon dioxide gas as the probe gas. While the SEM image analysis were done by using the SEM machine in the MCEM building. The magnified image of the char particles were obtained, later this images will be analysed by using the image processing software, the image-pro to obtained the particles diameter distribution before and after the gasification.

All of the data obtained from the surface area and SEM image analysis will be tabulated and compiled in the Microsoft excel and are going to be interpreted to define the change in the structural properties of the char along the course of the gasification. The pattern and trend which are going to be shown by the data will also lead to a hypothesis of the reaction mechanism of the carbon char with the gasifying gas which are the carbon dioxide and the oxygen.



3.2 Experimental Methods

Throughout the course of the experimental research project, several processes were conducted in order to obtain the necessary results. This includes obtaining the experimental material (mainly char) in order to proceed with the research.

3.2.1 Pyrolysis

Before gasification can be performed, char must be obtained from the pyrolysis process. Pyrolysis was performed using similar experimental procedures as the gasification process with the only difference being the gas used, which was nitrogen (N_2) in this process. This process also employs a 2 second residence time feeding tube which must be switched prior to the process.

- 1) Pyrolysis is first performed in order to obtain the necessary material before proceeding to the gasification process. The pyrolysis process was conducted using the drop-tube furnace. The drop-tube furnace diagram is shown below.
- 2) Firstly, the bottom of the reactor was firstly cleaned in order to reduce the amount of contaminant in the final product. This was done by utilizing a vacuum cleaner. The char receiving receiver which consisted of thimble filter, silicone nozzle, collector, and conical flask were assembled and connected to the bottom of the furnace.

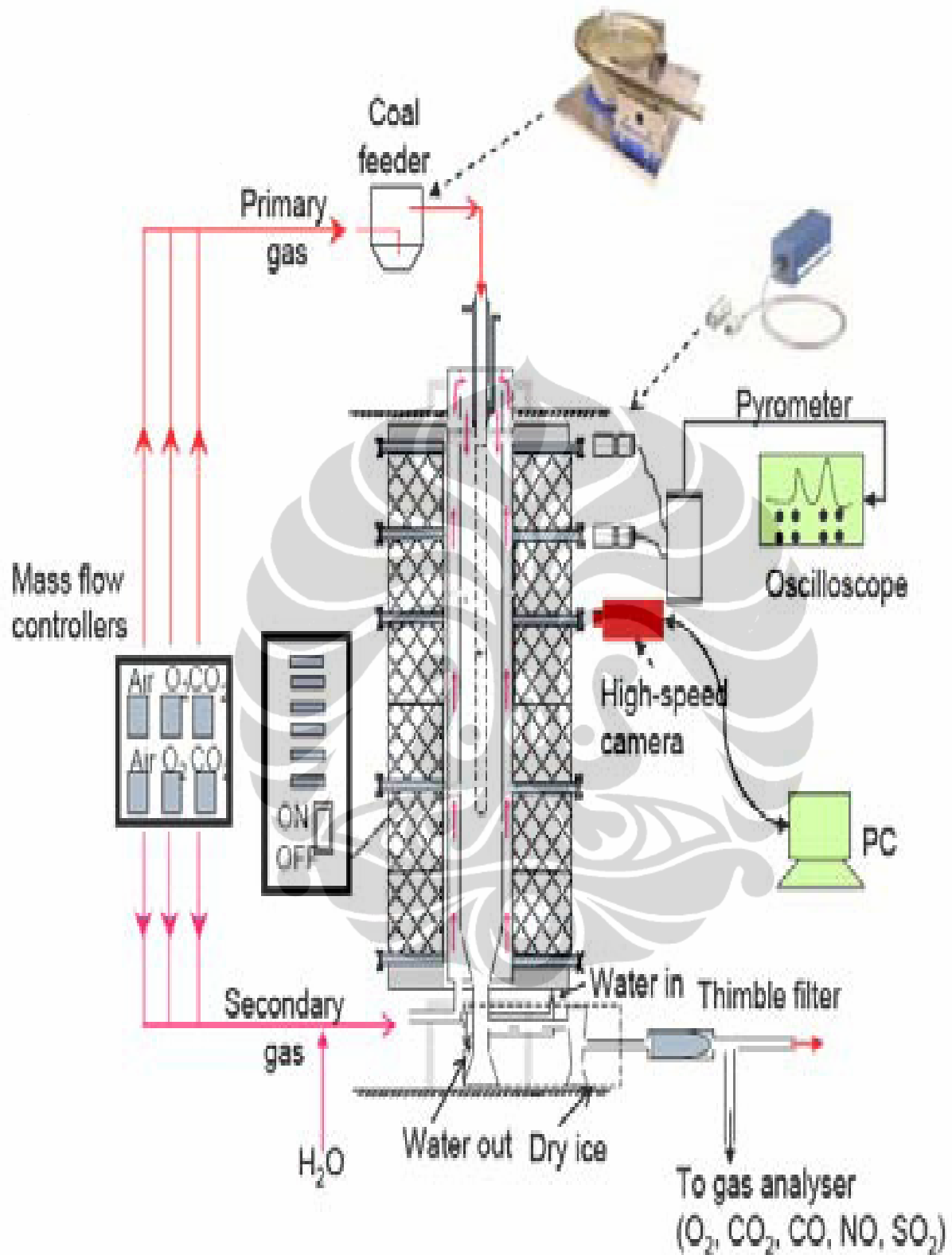


Figure 3.2.1.1 Drop Tube Reactor



Figure 3.2.1.2 Collecting Apparatus

Prior to connecting, the apparatus were cleaned using the air gun and the mass of each of the individual apparatus were weighed. After the necessary connection was completed, the collector and the housing that holds the thimble filter were immersed in dry ice in order to cool down the flue gas.



Figure 3.2.1.3 Collecting apparatus set up at the bottom of the reactor

- 3) The coal feeder (hopper) and the table were cleaned before any coal was fed into the reactor. This also includes the vacuum cover which will be used to keep the system in vacuum. This was to ensure that no dust particle was present during the experiment which could cause air leakage and the system would no longer be considered as a closed system.



Figure 3.2.1.4 Hopper at the top of the reactor after closing the lid

- 4) The mass of the coal was weighed, noted down and fed into the coal hopper. The coal hopper was then covered using the vacuum lid and care was taken in order to screw the lid in tightly to ensure no air leakage occurs during the experiment.
- 5) The gas was then turned on and calibrated with the 1:9 liter/min which is the top: bottom ratio. The system was then left for a few minutes in order for the gas to stabilize and purge the air inside the reactor.
- 6) After the system has stabilized, the hopper was then turned on and the time taken for the process to go to completion was taken down. After the feed hopper is empty, the hopper was then switched off and the char was then collected from the bottom of the reactor. Since dry ice was used, the apparatus were placed in the oven to dry. The apparatus were left in the oven for 2 hours. After the apparatus were sufficiently dried, they were then taken out and left out to cool to room temperature before the mass are taken again.
- 7) The char were then collected and placed in a beaker. The process was then repeated to obtain as much char as possible. After the process was completed for the day, the char receiving apparatus was placed in the furnace at 600°C overnight to burn off the black residue from the glue gas.

3.2.2 Sieving

Sieving was done in order to obtain the correct size range of the char. The range that was used in the experiment was in the range of $106\mu\text{m}$ - $153\mu\text{m}$. Before the sieving can be done, the mass of the unsieved char was weighed and taken down. After sieving, the mass of each of the ranges which were $<153\mu\text{m}$, $106\mu\text{m}$ - $153\mu\text{m}$ and $>106\mu\text{m}$ were weighed and taken down. This determines much was the allowable feed mass for the gasification process.



Figure 3.2.2.1 Sieving

3.2.3 Gasification

Gasification is a process where the char is reacted with CO_2 doped with oxygen (O_2). As stated previously, the gasification process will be done with the drop tube reactor. The process will be done with 3 different residence time which is at

- 2 seconds
- 4 seconds
- 6 seconds

The residence time was controlled by utilizing different feeding tubes at variable length and the drop tube reactor is of fixed length. The feeding tube consist of two layers of tube, with the cooling water in the outer tube so that no reaction occurs in the feeding tube until the

char, which is in the inner tube, is exposed to the reactor. At which each residence time will be done with three different gas compositions which will be employed by manually adjusting the gas flow rate. The gas flow rate control is shown below,

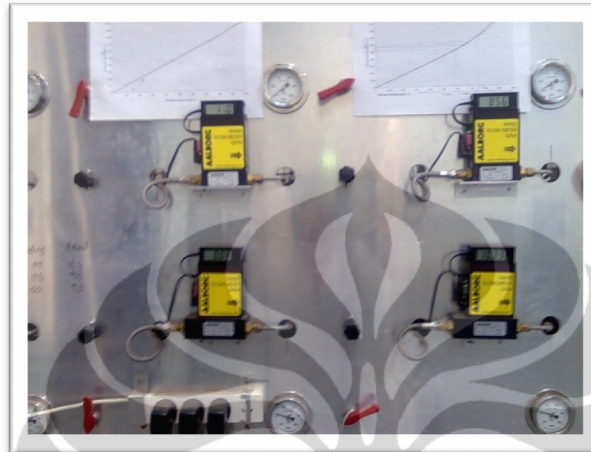


Figure 3.2.3.1 Gas manual valves

The gas compositions which will be used in this experiment are

- 1) 1% O₂ + balance CO₂
- 2) 5% O₂ + balance CO₂
- 3) Pure CO₂

A total of three runs were done for each parameter to obtain the average. After the gasification was done, the collecting apparatus was then kept in the oven at 120°C for a few hours to remove moisture. Subsequently, the apparatus was then taken out and left to cool down to ambient temperature before weighed to document the final mass. This final mass will be used to calculate the char yield which will be discussed further in the results section of the report. After weighing the apparatus, the char in the apparatus was then collected and kept in individually labeled coarse vials for further analysis.

3.2.4 Surface Area Analysis using ASAP 2010

Surface area analysis was done by using the ASAP 2010 machine. Before any analysis can be done, the samples were degasified to remove any excess moisture. The sample was degassed for approximately 4 hours before being analyzed. The image of the machine is shown below.

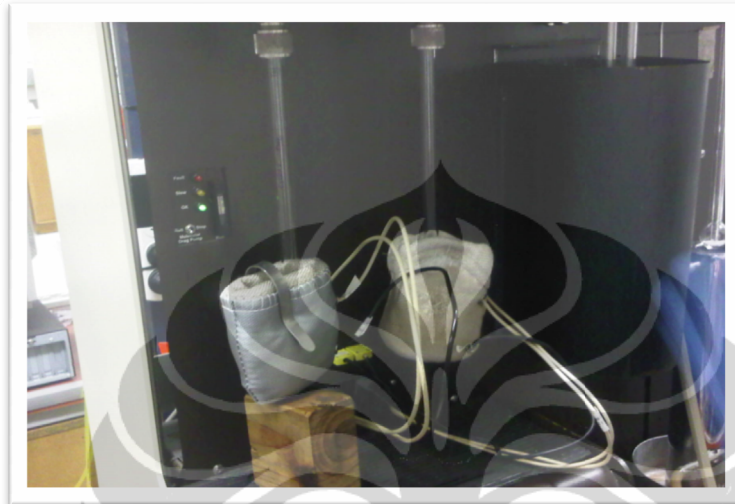


Figure 3.2.4.1 Degas process of the sample before analysis

This was done on all 10 samples including raw char to draw comparison between the char before and after gasification. From the results of the surface analysis, two samples were chosen for SEM imaging based on the biggest surface area difference.

3.2.5 SEM Imaging

Scanning Electron Microscopy or SEM imaging was done on two samples of which was raw char and the 100% CO₂ 4 second's sample. Before the SEM imaging can be done, the samples were placed on a carbon tape carefully on a metal disc. This is prior to coating the samples onto the carbon tape.

3.2.6 Diameter Analysis using Image-Pro

The images from the SEM imaging were then analyzed using the image pro for the diameter distribution. The general outline of the analysis is documented below

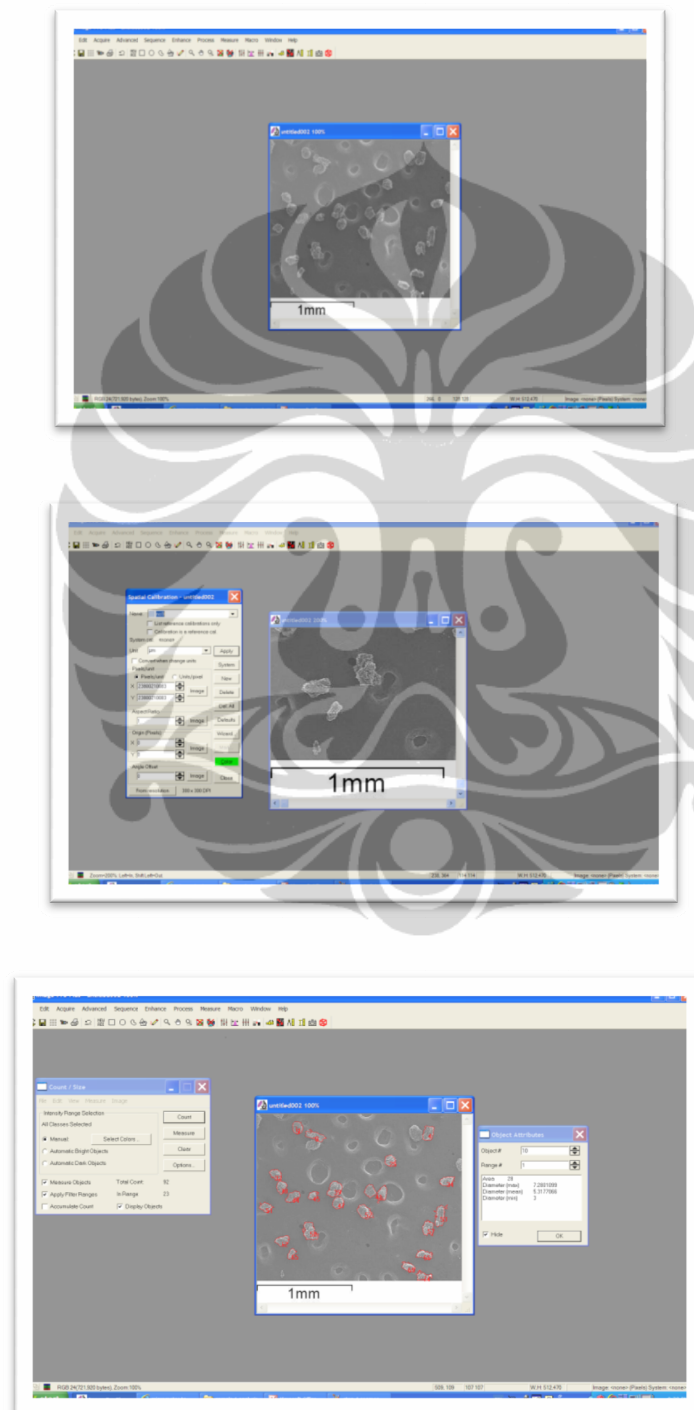


Figure 3.2.6.1 -3 : SEM Images Analysis using Image Pro

Finally, the particles are outlined and the measurement chosen for this particular analysis, as stated earlier was diameter. In this case, the mean diameter was taken as oppose to the min or max diameter. As shown in the image above, the red outlines are the particles in interest. The outlining of the particles was not perfect and therefore, some of outlines are not defined properly or of the background. In this case, the outlines can be chosen to be hidden. The measurements were then exported into an excel file.



Chapter 4

RESULT AND DISCUSSIONS

4.1 Char Yield Time Dependence

Below documents the char yield with dependence on residence time within the reactor. The char yield can be treated as an indirect measurement of the gasification reaction completion. It represents the amount of char which are not converted into gaseous product (syngas), therefore low char yield value means higher conversion of the reactant on the progressing reaction and vice versa. The char yield was calculated by taking the percentage of the char mass fed into the hopper over the difference between the initial and final mass of the collecting apparatus

Hypothesis was made upon the commencement of the experiment. It was predicted that longer residence time will translate to lower char yield. This hypothesis made upon the fact that, longer residence time means longer time for the char particles to react with the gasifying gas, thus there will be more char converted into gaseous product and less char residue will be collected at the bottom of reactor in a reaction with long residence time. This phenomenon is expected to happen to all sets of experiment s with different gasifying gas composition , although char yield decreasing magnitude are expected to be varies accordingly with the concentration of oxygen in the gasifying gas. The effect of oxygen concentration to the char yield will be discussed in another part of this report.

The table below summarizes the average char yield for each of the investigated condition on the gasification experiment, each of them represents one sets of experiment comprised of 3 runs of experiment. The full table of results documentation is attached to the appendix.

Table 4.1.1 Average results of the gasification process

	100% CO ₂	1% O ₂ + Balance CO ₂	5% O ₂ + Balance CO ₂
2 seconds	71.00633	78.9188	43.36241
4 seconds	38.73379	26.84148	33.03567
6 seconds	53.99309	60.21605	25.04626

These graphs show the char yield dependence on residence time.

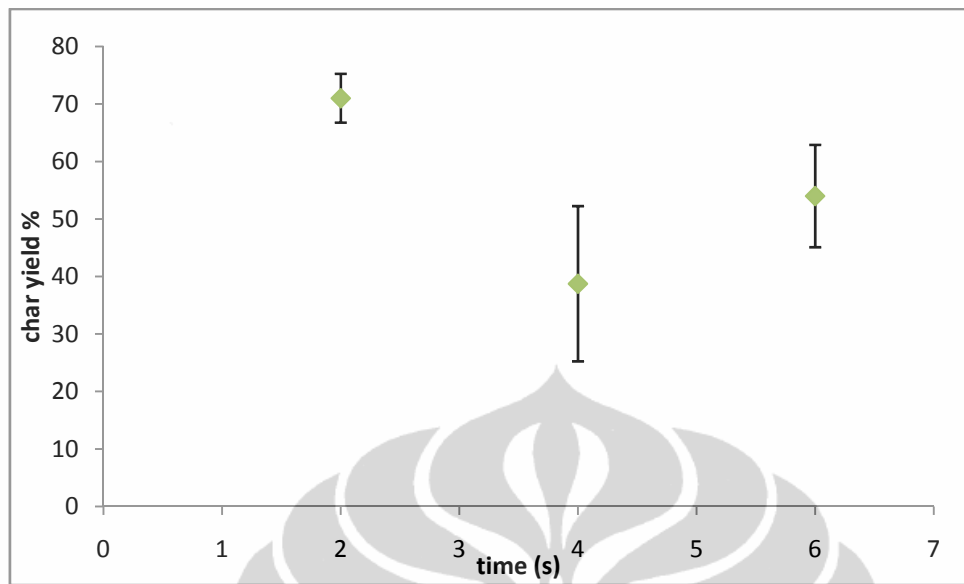


Figure 4.1.1 : Char Yield Results for Gasification using Pure CO_2

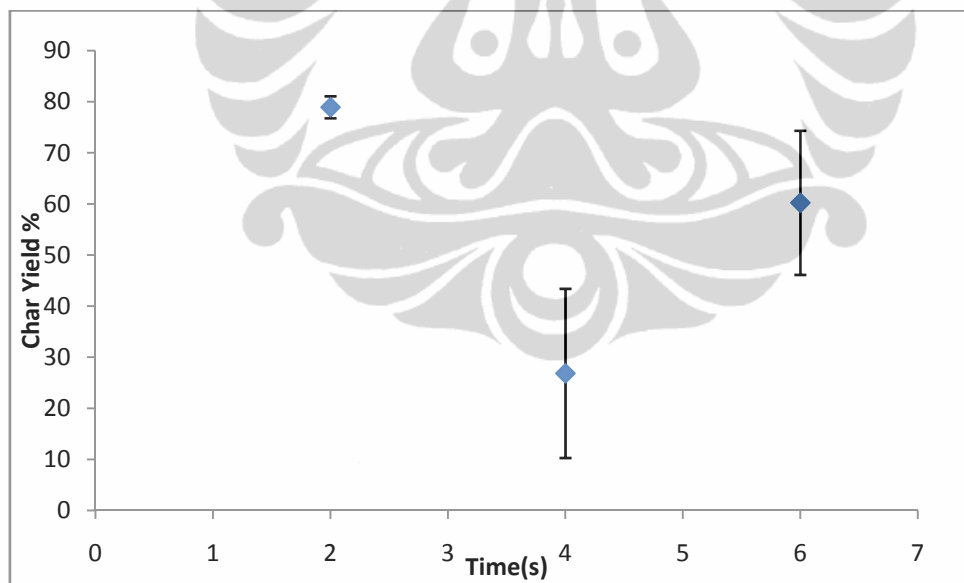


Figure 4.1.2 : Char Yield Results for Gasification using 1% O_2 and balance CO_2

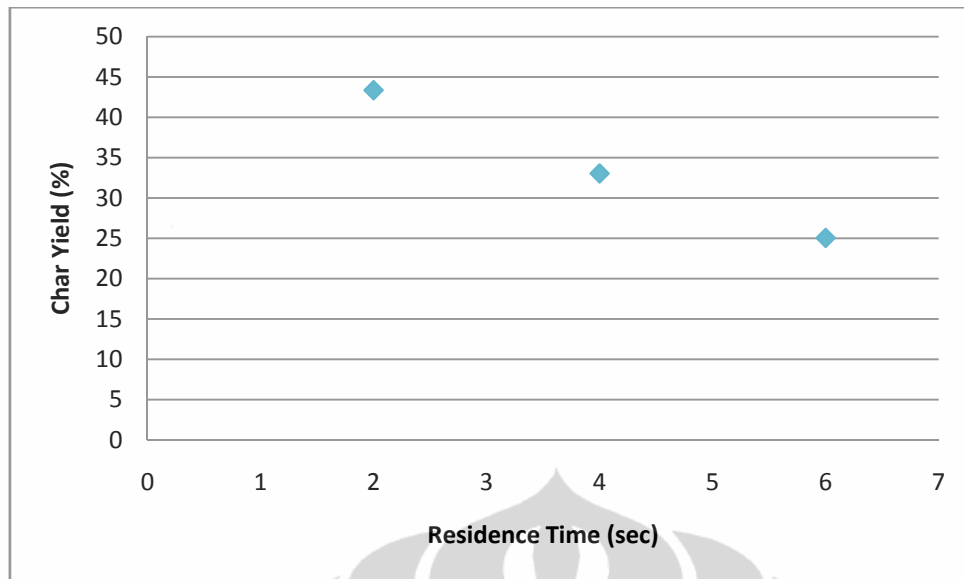


Figure 4.1.3 : Char Yield Results for Gasification using 5% O₂ and balance CO₂

As it can be seen here, it was expected that the char yield would decrease as the residence time increased. These results did not yield expected results for 100% CO₂ and 1%O₂+ CO₂. Although the general trends shows there is a decrease in the char yield as the residence time increasing on the pure CO₂ and 1 % CO₂ experiments but, there is a slight decrease of char yield on 4 seconds experiment and it continues to increase in 6 seconds experiment. This phenomenon does not agree with the hypothesis, so it is probable that there is a considerable amount of error occurred during the 4 seconds experiment. These suspicions are backed by the fact that there is a huge error bar for the 4 seconds residence time result. The error bars here represents the standard deviation of the average char yield from the three runs. This could be explained by the errors that might have occurred during running these experiments. Among these errors are,

- 1) Mishandling of the char during transferring. Spillage may also have occurred when moving the apparatus and thus affect the char yield percentage.
- 2) The error could have been attributed during the 4seconds residence time. Reruns could not be done on the 4 seconds residence time because of the broken tube.
- 3) Drop tube reactors are also notorious for non conformity in temperature distribution. This uneven temperature distribution may have affected the results⁽⁹⁾

- 4) There is a possibility that the char residue is carried away to the flue gas line, due to the thimble filter are not tighten adequately. It will affect the calculation of the char yield
- 5) Presence of trapped air within the gasifier. The air could disrupt the process by consuming the char during the gasification, therefore the amount of char yields are not represent the nature of the desired reaction

Re-run were done to minimize these error, but as mentioned above, the re-run cannot be done for the 4 seconds experiment because the feeding tube was broken, therefore re-run were done for the 6 seconds experiments instead.

4.2 Char Yield Oxygen Concentration Dependence

The effect of oxygen concentration on the gasifying gas composition was investigated by doing sets of experiment with different gasifying gas composition while the residence times were held constant. As in the previous experiment, the concept of char yield is once again used to measure the reaction completion.

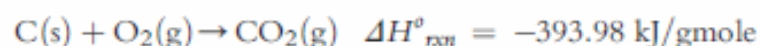
In this experiment, the gasifier and the gasifying gas are assumed to be clean and free from any impurities, therefore it is assumed that the reaction which are took place within the gasifier are only the reactions of the coal char with oxygen and carbon dioxide gas.

The reactions are as followings:

The Boudouard reaction, which is the main reaction, is the reaction of the char particles with the carbon dioxide gas



The oxygen related reactions, which are the Combustion and the partial oxidation.



In some sense, the oxygen and carbon dioxide reaction are compete with each other to react with the char but these reaction has very different characteristic. The oxygen reactions are

highly exothermic and reactive. It generates significant amount of heat while the primary reaction of carbon dioxide is endothermic and less reactive compared to the oxygen and char reaction. The sole purpose of the oxygen addition is to drive the primary reaction of the carbon dioxide forward by utilizing the heat produce from the oxygen reaction

Hypothesis was made upon the commencement of the experiment. It was predicted that the char yield will decrease as the oxygen concentration in the gasifying gas increased. This due to the afore mentioned fact that the oxygen is very reactive toward the coal char compared to the carbon dioxide, therefore for the same amount of time oxygen consumes more char than the carbon dioxide do, as a result the more oxygen in the gasifying gas will translate higher amount of char converted into gaseous product and lower char residue.

The result of the experiment regarding the char yield dependence to oxygen concentration is documented below.

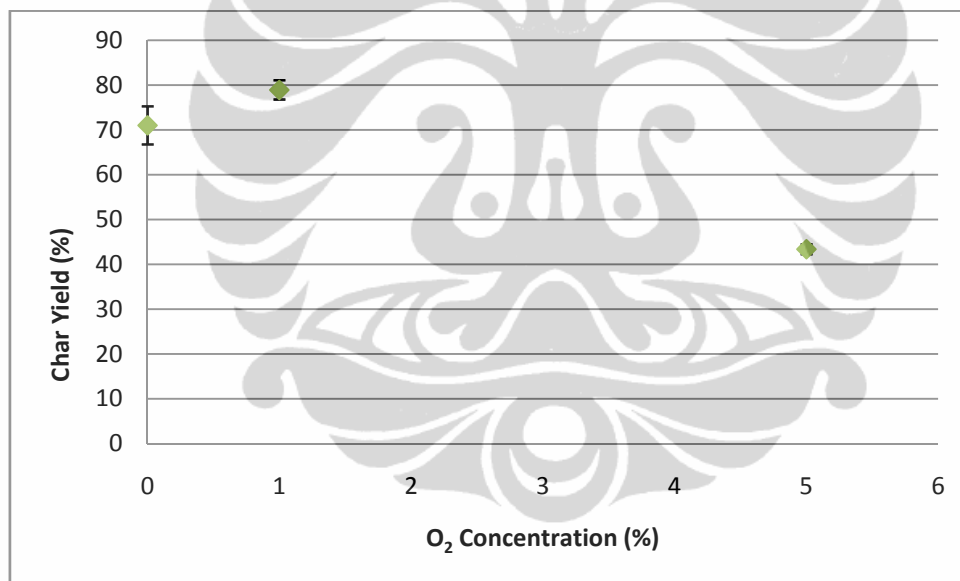


Figure 4.2.1 : Char Yield Results for 2 seconds Residence Time Gasification

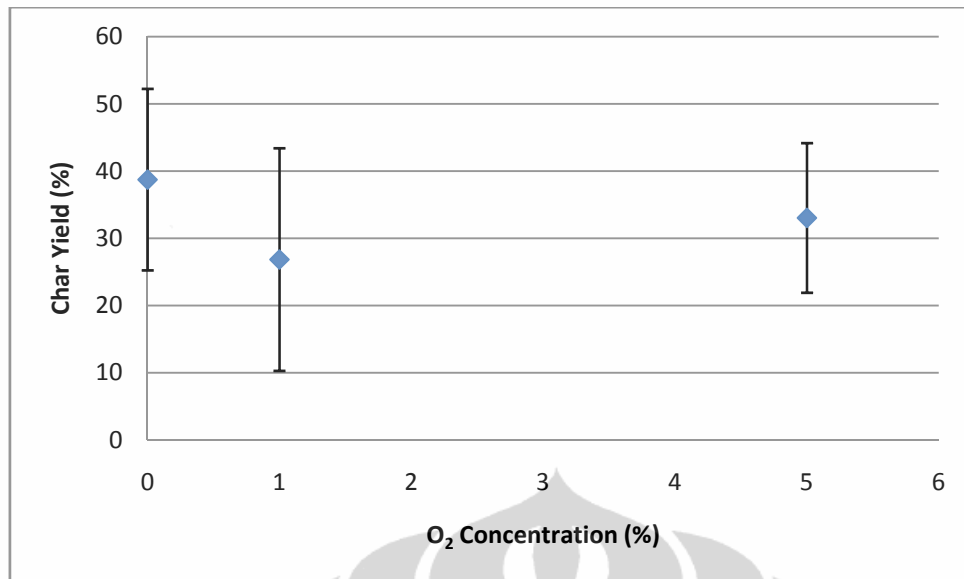


Figure 4.2.2 Char Yield Results for 4 seconds Residence Time Gasification

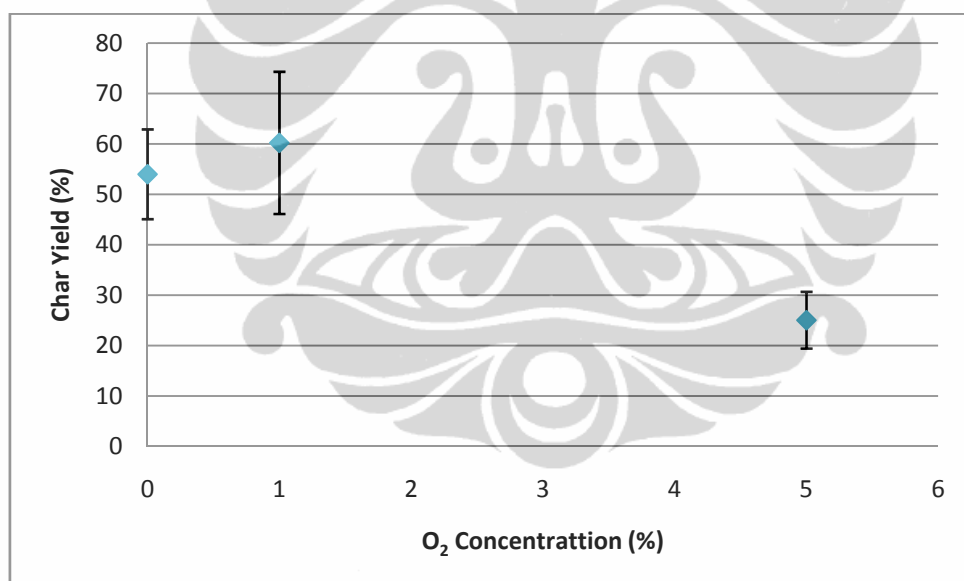


Figure 4.2.3 Char Yield Results for 6 seconds Residence Time Gasification

Generally, it can be seen that the char yield is decreasing as the oxygen concentration decreasing, for all of the investigated residence time. Therefore the hypothesis are proved to be true, although in all of the 1 % O₂ concentration experiments, the char yield a little bit off from the trend . At the 2 seconds and 4 seconds experiments the char yield at 1% O₂ concentration are slightly above the pure CO₂ experiments while it is significantly dropped at the 1 % O₂ and 4 seconds experiment. It is suspected that there is significance level of error

in the 1 % oxygen experiment. This might happen because the proportion of the oxygen flow and the carbon dioxide are maintained by manually adjusted valve which is very difficult to adjust when the required oxygen concentration is very small due to the fluctuation of the gas flow.

There are other types of error that might disrupt the result of this experiment. These errors are roughly similar to the afore mentioned errors in the char yield dependence of residence time section due to same method employed for both of this experiment.

4.3 Surface Area Analysis

From the surface area analysis using the ASAP 2010 analyzer, the BET surface area, pore volume and pore size was obtained from each of the samples. The graphs below documents the all the parameters obtained in accordance to the gas composition and residence time.

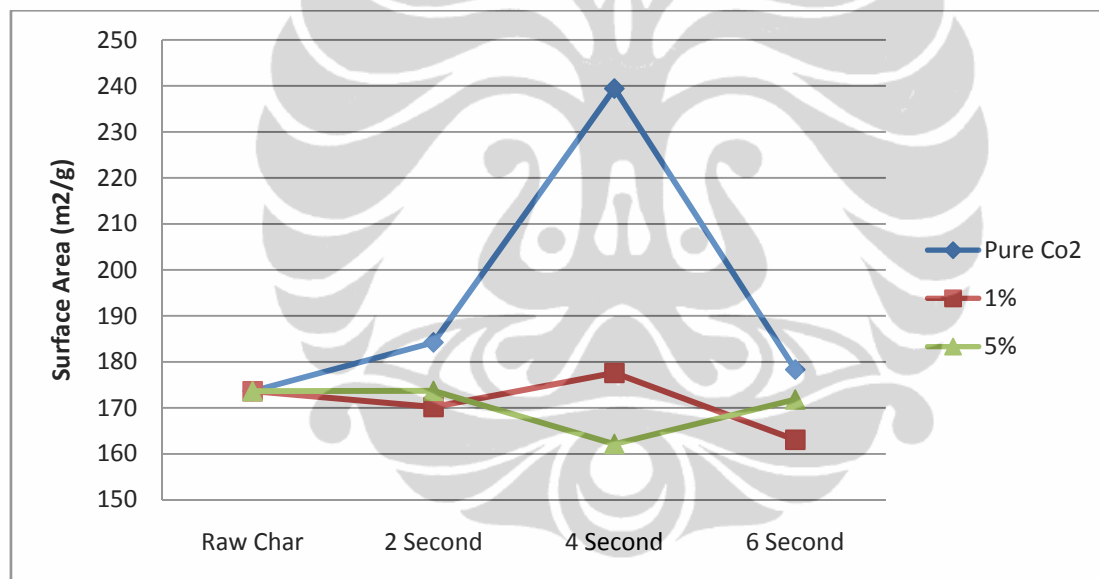


Figure 4.3.1 : BET Surface Area Analysis Data

The graph above shows the BET surface area of the char throughout the gasification process. The trend for both pure CO₂ and 1%O₂ + CO₂ indicates that at 1%O₂, a competing reaction occurs between CO₂ and O₂. In this case, as the trend are quite similar, albeit to a lesser magnitude for 1%O₂, the dominating reaction here is CO₂.

The highest peak occurs at 4s for both pure CO₂ and 1%O₂, which could possibly be explained by fragmentation that occurs at 4s. It was suspected that because of the porous nature of the char particle, bulk gas penetrates to the interior of the char through macro pores. As the reaction proceeds, gas accumulation from the reaction will cause an increased pressure

at the interior of the char and therefore, causes the char to fragment. At 6 seconds however, the particles were gasified and the char consumed, resulting in the decrease in pore surface area.

This was not the case in the 5%O₂ as it can be seen in the graph. The surface area decreases at 4 seconds instead of increasing as the previous samples did. As the char reacts more rapidly with O₂ than CO₂, the O₂ mainly reacts with the surface of the char. The surface of the char was therefore consumed and the surface area decreased ^[9]. At 6 seconds however, the surface area increased because of fragmentation due to gas accumulation in the interior of the char.

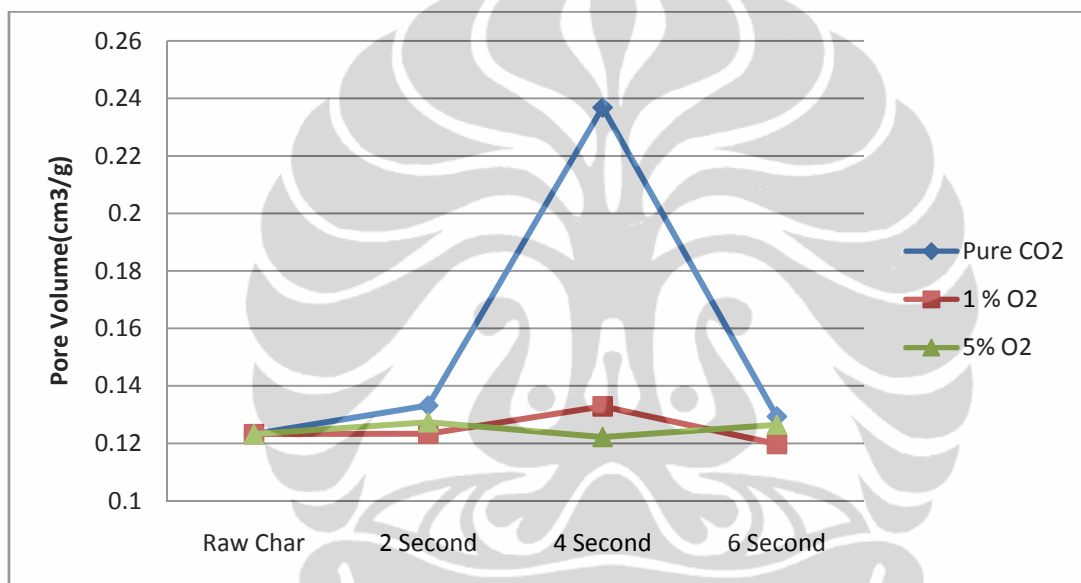


Figure 4.3.2 : Pore Volume Analysis Data

The pore volume reflects the surface area. As the surface area increased, so does the pore volume. As seen in the plot above, the trend is similar to the pore surface area plot.

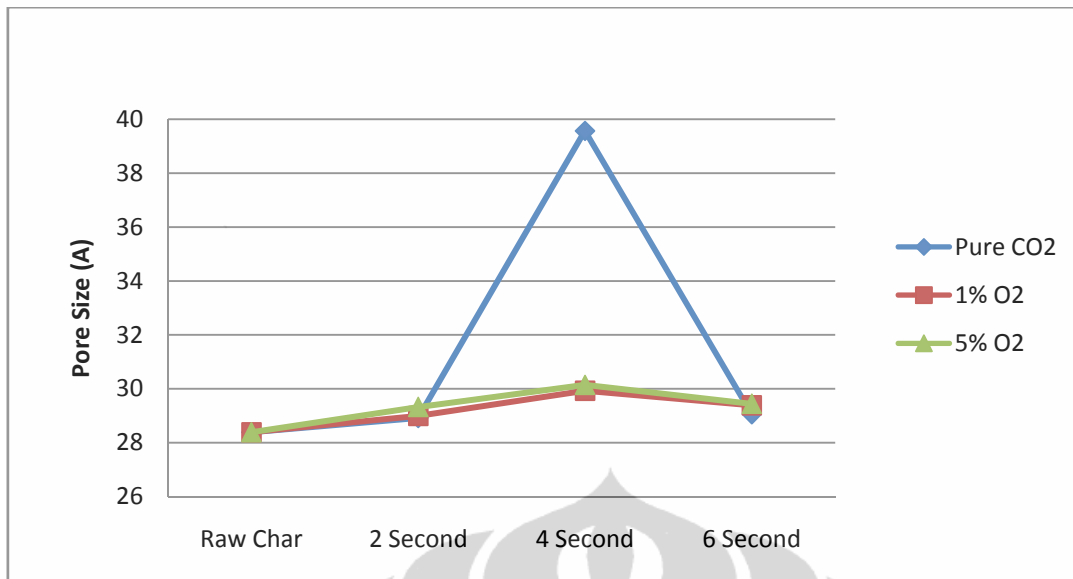


Figure 4.3.3 : Pore Size Analysis Data

The plot above suggests that the biggest pore size is at the 4s gasification which also was reflected in the pore surface area and volume. However, at 4s for 5% O₂, the pore size increased as opposed to decreasing as postulated in the pore surface area and volume. This is because the pore size does not reflect the number of pores, which was also taken into account when the surface area and volume was analyzed.

4.4 SEM Image Analysis with Image-Pro

The SEM image was analyzed in by using the image pro. Since the 4s 100% CO₂ presented with the highest change in pore surface area, it was chosen as comparison with the raw char. In this case, the char particles were assumed to be spherical in nature. The results of the diameter distribution were presented as frequency in a particular size ranges in micrometer.

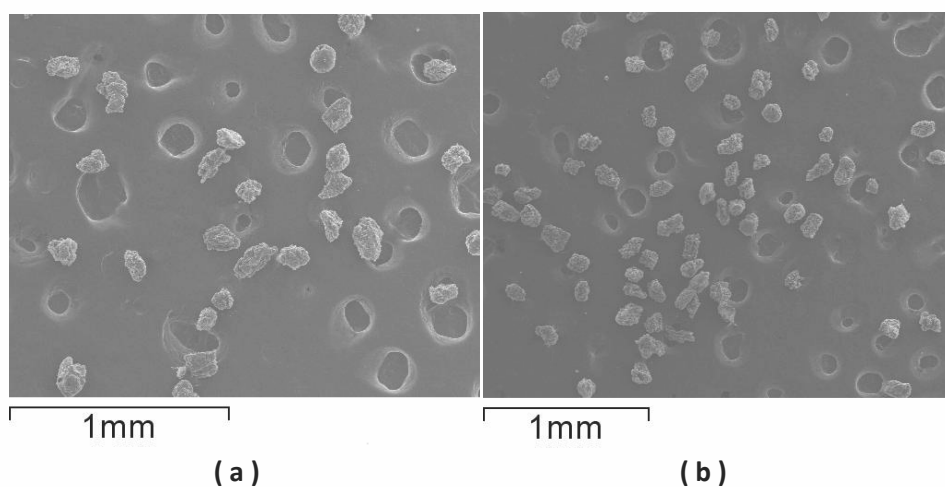


Figure 4.4.1 : SEM Image of Raw Char (a) and Residue Char (b)

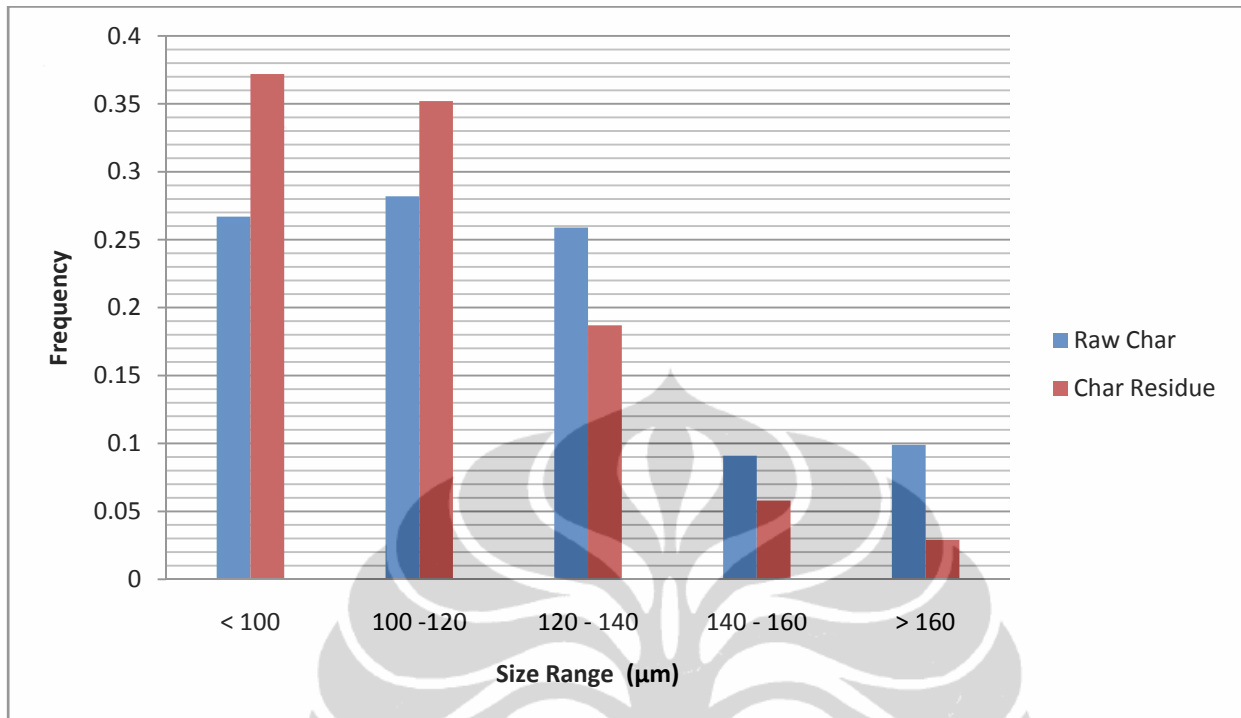


Figure 4.4.2 : Char Diameter Distribution

Comparing these results, as seen in the pie chart, there was an increased frequency in the smaller ranges of the diameter distribution in the samples after gasification. This explains that fragmentation does occur after the gasification.

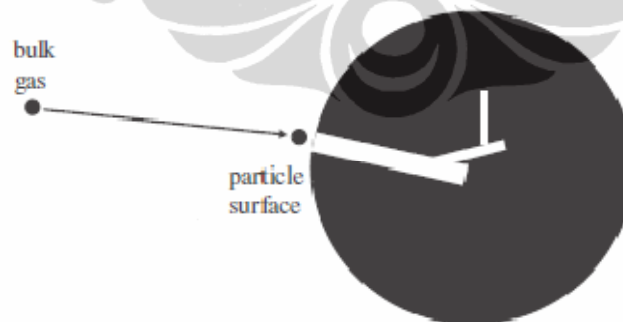
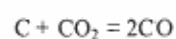


Figure 4.4.5 Image depicting the bulk gas entering the macropore, mesopore and finally the micropore

It is understood that char fragmentation occurs as a result of gas accumulation in the char interior. This happens because there is a higher gas production than consumption as seen in the governing Boudouard Reaction [21]

Boudouard reaction



(R5-4)

+171

As the gas enters the particle interior through the macropore, it will make its way to the mesopore and to the micropore before finally adsorbing to the reaction site^[2]

4.5 Application and Contribution of Results

The overall result of the experiment has advanced the understanding of the characteristics of brown coal gasification. From the results of the experiment, it was found that the oxygen concentration could be used to drive the reaction forward. This was shown in the char yield dependence on oxygen concentration where the char yield decreases, producing more syngas as the oxygen concentration was increasing. As this was the case, this particular combination could be used to improve the efficiency of syngas production by means of brown coal gasification.

4.6 Limitation, improvements and further studies

There were some limitations in the brown coal gasification in this study. Some of them were,

- 1) The Alkali Alkaline Earth Metal (AAEM) which is notoriously abundant particularly in the Victorian brown coal was not considered in this study. The effect of pressure and also temperature was also not in the scope of this particular study.
- 2) Throughout the study, the char particles were assumed to be spherical in nature.
- 3) The gas mixture was to manually calibrate and therefore may have contributed in the error that occurred in this study.

Some improvements were proposed for future studies in order to refine the results of the study. These were

- 1) Utilizing premixed gasses to reduce the errors in the experiment when conducting research with small concentrations. In this case, gas canister with premixed CO₂ and O₂ gas could be used in order to eliminate errors associated with manual calibrations.
- 2) Conducting acid coal washing in order to investigate the effect of AAEM on the char yield percentages.
- 3) Conducting the research with different types of gasifying agent such as O₂ + H₂O (Steam) which according to some studies, are a better combination (Bell A D, et al,

2011). Other than that, the optimum ratio of O_2+CO_2 could also be investigated to further improve the efficiency of this combination of gasifying agent.

- 4) Investigating the effects of the gasifying agent in accordance with different temperature and pressure in order to obtain the optimum working parameters for syngas production
- 5) Conduct flue gas analysis to investigate the composition of the gas produced whilst using the CO_2/O_2 gasifying agent.
- 6) Employing different size ranges and its effects during gasification.



CHAPTER 5

CONCLUSION

From the results of the studies and experiments on the char yield dependence on residence time and oxygen concentration on the gasifying agent, the followings facts are known.

- Longer residence time in the reactor translate to lower char yield
- Char yields are generally decreases with the increase in the oxygen concentration

Lowest char yield achieved at 5% O₂ gasifying gas composition and 6 second residence time, where char yield goes to as low as 45 % to 25 %.

The structural changes were examined by using BET method to calculate surface area, pore volume and size while size distribution before and after gasification wre examined using SEM imaging. The aforementioned experiments yield severals result.

- The structural parameters (surface area, pore volume, pore size) shows similar trend over the course of reaction
- In CO₂ dominated reactions, surface area increase significantly halfway during reaction and subsequently dropped afterwards
- In O₂ dominated reaction surface area steadily decreasing while showing little fluctuation
- SEM imaging suggest that fragmentation does occured during gasification process, this fact is generally true for gasification with CO₂ as gasifying gas

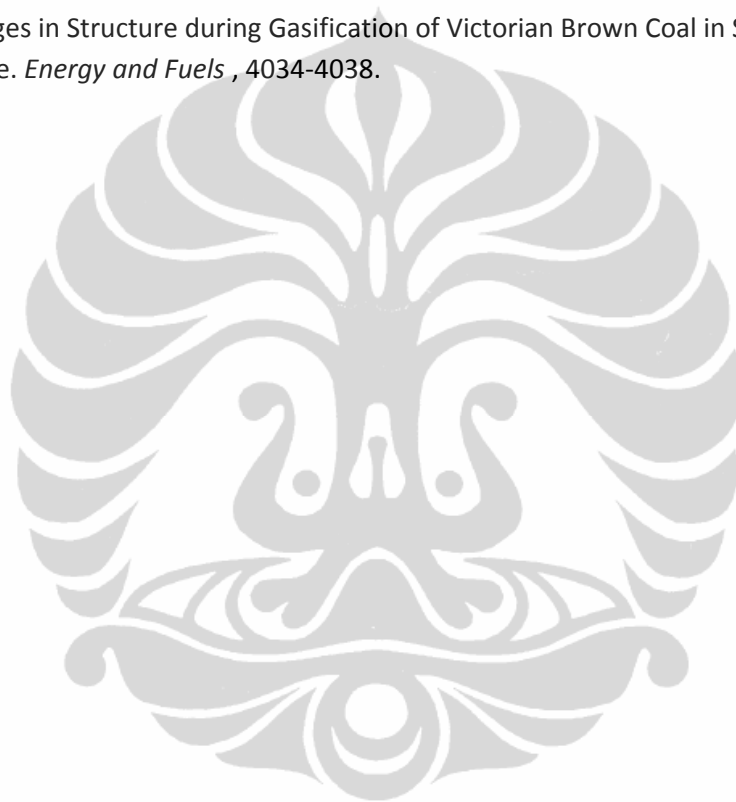
In CO₂ dominated reaction, the surface area goes as high as 240 m²/g to 180 m²/g due to char fragmentation and promptly decrease to around 170 m²/g, while in O₂ reaction the surface area steadily dropped to around 160 m²/g. SEM analysis shows considerable increase in the frequency of char particles which diameter smaller than 120 microns (from 0.27 to 0.36 for particle smaller than 100 microns and from 0.28 to 0.35 for particle at 100 to 120 microns). While there is a noticeable decrease in the frequency of larger particle (0.26 to 0.19 for 120 to 140 microns, 0.09 to 0.06 for 140 to 160 microns and 0.1 to 0.03 for larger than 160 microns)

The analysis and result of both expeiment improved the understanding of gasification characteristics of brown coal which can be used for future studies in the area.

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APPENDIX

A1. Surface Area Analysis Data

Table A.1.1 : Surface Area analysis data for Raw Char

Parameter	Raw Char		
	>153	<105	105-103
BET Surface Area(m ² /g)	149.8051	175.7287	173.6199
Pore Volume (cm ³ /g)	0.108879	0.126609	0.123218
Pore Size (Angstrom)	29.072	28.8191	28.388

Table A.1.2 : Surface Area analysis data for 2 second residence time

Parameter	2 Second		
	CO ₂	1% O ₂	5% O ₂
BET Surface Area(m ² /g)	184.2269	170.1915	173.6943
Pore Volume (cm ³ /g)	0.133185	0.123359	0.127323
Pore Size (Angstrom)	28.9177	28.9931	29.3211

Table A.1.3 : Surface Area analysis data for 4 second residence time

Parameter	4 Second		
	CO ₂	1% O ₂	5% O ₂
BET Surface Area(m ² /g)	239.4247	177.5901	162.1305
Pore Volume (cm ³ /g)	0.236856	0.132875	0.122187
Pore Size (Angstrom)	39.5709	29.9286	30.1453

Table A.1.4 : Surface Area analysis data for 6 second residence time

Parameter	6 Second		
	CO2	1% O2	5% O2
BET Surface Area(m²/g)	178.3109	163.0634	171.8244
Pore Volume (cm³/g)	0.1293	0.119801	0.126463
Pore Size (Angstrom)	29.055	29.3876	29.44



A.2 Gasification Experiment Data

Table A.2.1 : Gasification result for 2 second residence time with pure CO₂

Gasification of Hi-ash Brown Coal Char (105-153 micron)			
2 Second Residence Time			
Pure CO ₂			
Date	13/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	1.2968	1.3131	1.4244
Run Time	5:43	5:40	5:46
Reactor Temp			
Zones 1-2-3	424,506, 657	422, 503, 665	412, 506, 664,
Zones 4-5-6	970, 980, 980	974, 980, 980	976, 980, 980
Top Gas(mL/min)			
O ₂			
CO ₂	880	900	896
Bottom Gas(L/min)			
CO ₂	10.31	10.3	10.42
Initial Mass (g)			
Flask	117.2518	112.1822	107.1357
Collector	67.7246	65.1514	65.7191
Nozzle	24.3378	27.614	24.6209
Silicone Tube	15.673	15.0973	14.7976
Thimble Filter	3.0852	2.9997	3.3909
Final Mass (g)			
Flask	118.115	113.0213	108.1265
Collector	67.7246	65.1513	65.7211
Nozzle	24.3383	27.6163	24.6221
Silicone Tube	15.6624	15.0959	14.7985
Thimble Filter	3.2013	3.04	3.3976
Char Residue			
Coarse Vial	0.8553	0.8816	0.9796
Data	0.9798	0.8817	1.0016

Table A.2.2 : Gasification result for 2 second residence time with 1 % O₂ and balance CO₂

1% O ₂ + CO ₂			
Date	13/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	0.9918	0.9843	
Run Time	2:11	2:39	
Reactor Temp			
Zones 1-2-3	332, 399, 500	335, 397, 500	
Zones 4-5-6	700, 980, 980	700, 980, 980	
Top Gas(mL/min)			
O₂	109	110	
CO₂	870	870	
Bottom Gas(L/min)			
CO₂	10.32	10.37	
Initial Mass (g)			
Flask	107.1159	117.2613	
Collector	67.9221	67.7166	
Nozzle	24.3343	24.6206	
Silicone Tube	15.7324	15.4913	
Thimble Filter	3.1185	3.103	
Final Mass (g)			
Flask	107.881	117.9899	
Collector	67.9228	67.7784	
Nozzle	24.3361	24.622	
Silicone Tube	15.6951	15.4457	
Thimble Filter	3.0196	3.0245	
Char Residue			
Coarse Vial	0.748	0.728	
Data	0.7676	0.7918	

Run 3 was not conducted because of time constraints

Table A.2.3 : Gasification result for 2 second residence time with 5 % O₂ and balance CO₂

5% O₂ + CO₂			
Date	13/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	1.0011	0.9431	
Run Time	2:58	2:48	
Reactor Temp			
Zones 1-2-3	342, 399, 500	341, 401, 500	
Zones 4-5-6	700, 9980, 981	700, 980, 981	
Top Gas(mL/min)			
O₂	509	500	
CO₂	561	559	
Bottom Gas(L/min)			
CO₂	10.33	10.33	
Initial Mass (g)			
Flask	112.15	107.1168	
Collector	65.1527	67.9206	
Nozzle	27.6144	24.3352	
Silicone Tube	15.0244	16.106	
Thimble Filter	3.0259	3.3064	
Final Mass (g)			
Flask	112.5703	107.5311	
Collector	65.1533	67.9213	
Nozzle	27.6198	24.3365	
Silicone Tube	14.9492	16.0278	
Thimble Filter	2.9823	3.2524	
Char Residue			
Coarse Vial	0.3943	0.399	
Data	0.4263	0.4163	

Run 3 was not conducted due to time constraints

Table A.2.4 : Gasification result for 4 second residence time with pure CO₂

Gasification of Hi-ash Brown Coal Char (105-153 micron)			
4 Second Residence Time			
Pure CO₂			
Date	4/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	1.5405	1.0416	0.8917
Run Time	7:12	6:23	5:21
Reactor Temp			
Zones 1-2-3	525 ,800 ,1000	512, 800, 1001	535, 800, 1000
Zones 4-5-6	980, 980, 980	980, 980, 982	980, 980, 980
Top Gas(mL/min)			
O₂	0	0	0
CO₂	906	909	913
Bottom Gas(L/min)			
CO₂	10.4	10.38	10.54
Initial Mass (g)			
Flask	117.2237	107.1897	113.3776
Collector	64.4367	65.7763	65.1442
Nozzle	24.6243	27.6231	24.4398
Silicone Tube	14.8221	14.5115	12.2531
Thimble Filter	3.0091	3.0764	3.0236
Final Mass (g)			
Flask	118.2587	107.5837	113.6934
Collector	64.4399	65.7852	65.1488
Nozzle	24.4279	27.6331	24.4476
Silicone Tube	14.7944	14.5022	12.2434
Thimble Filter	2.9568	3.0541	3.0195
Char Residue			
Coarse Vial	0.805	0.403	0.2252
Data	0.8418	0.4129	0.3282

Table A.2.5 : Gasification result for 4 second residence time with 1 % O₂ and balance CO₂

1% O ₂ + CO ₂			
Date	5/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	0.64229	0.6523	0.6627
Run Time	3:27	3:43	3:53
Reactor Temp			
Zones 1-2-3	520,800,1000	524,801,1000	532, 800, 1000
Zones 4-5-6	980,980,980	980,980,981	980,980,982
Top Gas(mL/min)			
O₂	100	98	98
CO₂	886	885	884
Bottom Gas(L/min)			
CO₂	10.4	10.41	10.31
Initial Mass (g)			
Flask	117.2421	107.1206	113.3616
Collector	64.4985	65.7164	65.1552
Nozzle	24.6226	27.6136	24.338
Silicone Tube	14.8588	14.5033	12.26
Thimble Filter	3.1519	3.1876	3.2063
Final Mass (g)			
Flask	117.4588	107.345	113.3935
Collector	64.5031	65.7345	65.168
Nozzle	24.6242	27.6186	24.3407
Silicone Tube	14.8553	14.5037	12.2644
Thimble Filter	3.0274	3.0829	3.0978
Char Residue			
Coarse Vial	0.2081	0.2151	0.2245
Data	0.2229	0.2479	0.0518

Table A.2.6 : Gasification result for 4 second residence time with 5 % O₂ and balance CO₂

5% O ₂ + CO ₂			
Date	5/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	0.6397	0.6487	0.6686
Run Time	3:22	3:50	4:40
Reactor Temp			
Zones 1-2-3	520,800,1000	524,801,1000	532,800, 1000
Zones 4-5-6	980,980,980	980,980,981	980,980,982
Top Gas(mL/min)			
O₂	452	486	506
CO₂	547	565	557
Bottom Gas(L/min)			
CO₂	10.3	10.5	10.4
Initial Mass (g)			
Flask	117.306	107.1275	112.229
Collector	64.521	65.734	65.1539
Nozzle	24.6219	27.6133	24.3367
Silicone Tube	14.8536	14.5008	12.255
Thimble Filter	2.954	2.987	3.092
Final Mass (g)			
Flask	117.5042	107.1621	112.2438
Collector	64.587	65.7412	65.1637
Nozzle	24.6225	27.6166	24.339
Silicone Tube	14.8687	14.6012	12.261
Thimble Filter	3.0623	3.0915	3.1943
Char Residue			
Coarse Vial	0.2581	0.038	0.1043
Data	0.3882	0.25	0.1352

Table A.2.7 : Gasification result for 6 second residence time with pure CO₂

Gasification of Hi-ash Brown Coal Char (105-153 micron)				
6 Second Residence Time				
Pure CO₂				
Date	11/04/2011			
	Run 1	Run 2	Run 3	Re-run 1
Mass In Hopper (g)	0.6288	0.6369	0.5272	0.6649
Run Time	3:06	3:00	2:26	2:43
Reactor Temp				
Zones 1-2-3	1000,1000,1000	1000,1000,1000	1000,1000,1000	1000,1000,1000
Zones 4-5-6	980,980,980	980,980,977	980,980,981	980,980,981
Top Gas(mL/min)				
O₂				
CO₂	900	907	904	902
Bottom Gas(L/min)				
CO₂	10.4	10.37	10.14	10.45
Initial Mass (g)				
Flask	112.1766	107.1112	117.2485	112.2192
Collector	65.1531	65.7188	65.4537	65.1785
Nozzle	27.6145	24.6224	24.3375	27.694
Silicone Tube	14.8254	15.7862	15.2203	14.8218
Thimble Filter	2.785	3.023	3.1128	2.8818
Final Mass (g)				
Flask	-	107.4223	117.5635	112.4275
Collector	-	65.7197	65.4546	65.1575
Nozzle	-	24.6428	24.3419	27.6152
Silicone Tube	-	15.8032	15.2232	14.8228
Thimble Filter	-	3.3095	3.22	3.069
Char Residue				
Coarse Vial		0.3344	0.335	0.3054
Data		0.6359	0.4304	0.3965

Table A.2.8 : Gasification result for 6 second residence time with 1 % O₂ and balance CO₂

1% O ₂ + CO ₂			
Date	10/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	0.6714	1.318	0.7772
Run Time	3:18	6:04	3:51
Reactor Temp			
Zones 1-2-3	1000,1000,1000	1000,1000,1000	1000,1000,1000
Zones 4-5-6	980,980,981	980,981,979	980,980,981
Top Gas(mL/min)			
O₂	85	109	105
CO₂	870	865	864
Bottom Gas(L/min)			
CO₂	10.21	10.25	10.2
Initial Mass (g)			
Flask	112.1930	117.2452	107.1215
Collector	65.4522	65.7172	65.1524
Nozzle	24.3367	24.6221	27.6144
Silicone Tube	15.6964	14.8194	15.1411
Thimble Filter	2.8631	2.929	2.9781
Final Mass (g)			
Flask	112.543	117.83	107.4682
Collector	65.4539	65.727	65.1546
Nozzle	24.3441	24.6257	27.6213
Silicone Tube	15.7044	14.8592	15.1439
Thimble Filter	3.0035	3.0445	2.9917
Char Residue			
Coarse Vial	0.5075	0.7535	0.3722
Data	0.217	1.044	0.33722

Table A.2.9 : Gasification result for 6 second residence time with 5 % O₂ and balance CO₂

5% O ₂ + CO ₂			
Date	13/04/2011		
	Run 1	Run 2	Run 3
Mass In Hopper (g)	1.2103	1.3168	1.3104
Run Time	5:30	5:34	5:31
Reactor Temp			
Zones 1-2-3	1000,1000,1000	1000,1000,1000	1000,1000,1000
Zones 4-5-6	980,980,981	980,980,980	980,980,980
Top Gas(mL/min)			
O₂	446	386	435
CO₂	493	536	555
Bottom Gas(L/min)			
CO₂	10.16	10.64	10.24
Initial Mass (g)			
Flask	112.1853	107.1209	117.2441
Collector	67.7237	65.1526	65.7195
Nozzle	24.6223	24.3366	27.6149
Silicone Tube	14.8096	15.1301	15.6883
Thimble Filter	3.028	3.0067	3.1398
Final Mass (g)			
Flask	112.8156	107.2452	117.4287
Collector	67.7261	65.1539	65.7216
Nozzle	24.6231	24.3379	27.6155
Silicone Tube	14.8045	15.1052	15.67
Thimble Filter	3.1719	3.1242	3.3204
Char Residue			
Coarse Vial	0.6093	0.1183	0.236
Data	0.7774	0.2444	0.3679

Table A.2.10 : Gasification result for 6 second residence time Re-run

Rerun 6seconds				
1% O2 + CO2			5% O2 + CO2	
Date	5/03/2011		Date	5/03/2011
	Run 1	Run 2		Run 1
Mass In Hopper (g)	0.9205	0.8471	Mass In Hopper (g)	1.2153
Run Time	1:58	6:04	Run Time	5:30
Reactor Temp			Reactor Temp	
Zones 1-2-3	1000, 996, 1000	1000, 997, 1000	Zones 1-2-3	1000,1000,100 0
Zones 4-5-6	980,980,981	980, 980, 980	Zones 4-5-6	980, 980, 980
Top Gas(mL/min)			Top Gas(mL/min)	
O2	100	100	O2	487
CO2	878	868	CO2	550
Bottom Gas(L/min)			Bottom Gas(L/min)	
CO2	10.31	10.33	CO2	10.45
Initial Mass (g)			Initial Mass (g)	
Flask	113.3267	107.115 6	Flask	117.2428
Collector	67.7276	65.1595	Collector	67.7204
Nozzle	27.6136	24.6247	Nozzle	24.3369
Silicone Tube	15.3141	14.9068	Silicone Tube	16.019
Thimble Filter	3.4145	3.096	Thimble Filter	3.3497
Final Mass Mass (g)			Final Mass Mass (g)	
Flask	113.9233	107.655 8	Flask	117.5803
Collector	67.7215	65.159	Collector	67.7293
Nozzle	27.6183	24.6259	Nozzle	23.1715
Silicone Tube	15.3066	14.932	Silicone Tube	16.009
Thimble Filter	3.3007	2.999	Thimble Filter	3.2513
Char Residue			Char Residue	
Coarse Vial	0.5315	0.4128	Coarse Vial	0.2931
Data	0.5952	0.5666	Data	0.3464

Reruns were conducted on the 6 seconds residence time under these conditions