

Evaluation of Carbon Dioxide sequestration in Malaysian coal seams

by

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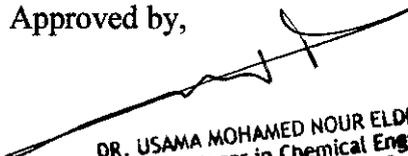
CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.



(Hassan Ahmed Mohamed Mady)

ABSTRACT

Sequestration projects are attempting to prevent the release of large quantities of CO₂ into the atmosphere from fossil fuel use in power generation and other industries by capturing CO₂, transporting it and ultimately, pumping it into underground geologic formations to securely store it away from the atmosphere. It is a potential means of mitigating the contribution of fossil fuel emissions to global warming. The process is based on capturing carbon dioxide (CO₂) from large point sources, such as fossil fuel power plants, and storing it where it will not enter the atmosphere.

The interactions of CO₂ with coal will be investigated under a set of conditions to determine the effects of the nature of the coal and the sequestration environment including parameters such as rank and moisture content of the coal, the temperature, and pressure, And the effect of these parameters on the CO₂ adsorption capacity. Some sets of experiments are conducted based on the coal collected from two different basins across Malaysia and the best isotherm obtained based on the best adsorption capacity is selected to be the major basin where the carbon dioxide gas is to be sequestered.

Adsorption experiments were favorable at high pressure and low temperature conditions and the Temkin isotherm was selected to represent the adsorption behavior.

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Abbreviations and Nomenclatures

CCS – Carbon capture and storage

EDX– Energy dispersive X-ray

CBM – Coal bed Methane

Ads – Adsorbed amount

XRD – X-Ray Diffractor

FTIR – Fourier transform infrared spectroscopy

FESEM – Field Emission Scanning Electron Microscope

CHAPTER 1

INTRODUCTION

1.1 Global warming and CO₂ level in atmosphere

The major contributor to the green house gas Carbon dioxide (CO₂) was seen to have increased in its concentration in the atmosphere over the years. That will highly give a great concern to the global warming effect, which will cause worldwide problems such as ozone reduction and desertification. Regarding the mitigation techniques to control the increase in CO₂ concentration, research has been conducted in many areas. Among them is the sequestration of CO₂, which generally means taking control over the concentration of CO₂ in the atmosphere. There are many ways of sequestration techniques and in this report we will be focusing to the CO₂ sequestration is geological sequestration. This process is carried out by using the natural porosity of geological formations to act as reservoirs for long term CO₂ storage. Not only is geologic sequestration thought to have the largest potential for near-term application but it has also been recognized as an environmentally attractive method to reduce the amount of greenhouse gas emission.

In this day and age, addressing climate change has become central for every country to pursue in sustaining the global environment for our future generation. At the United Nations Climate Change Conference 2009 in Copenhagen (COP15), Malaysia aspired to reduce forty percent of carbon emission by the year of 2020 as compared with its 2005 levels (Bernama, 18 December 2009). In line with Malaysian Government effort above, it is necessary for urban areas in Malaysia experiencing rapid urbanization (70% of urban population with 3% annual rate of increase) to be regulated and minimize its carbon emission. Ho et al. (2010) noted that these urban developments are responsible for 70% of national carbon emission.

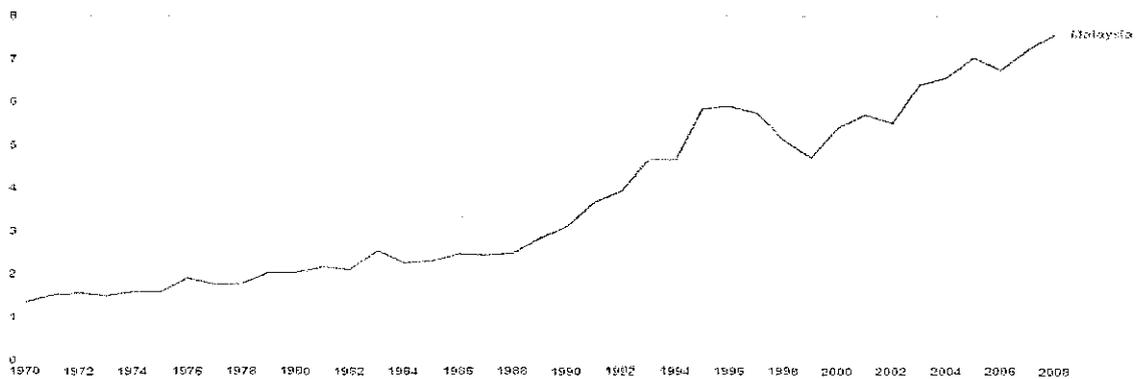


Figure 1. Graphical representation of CO₂ emissions in Malaysia per capita

Carbon dioxide emissions to the atmosphere can be controlled by reducing its production and release into the atmosphere, or by capturing and disposing of the produced CO₂ in a safe manner (sequestration)[1,2]. Various CO₂ sequestration options have been proposed, including placement in the deep oceans; placement in geologic formations (deep saline aquifers, abandoned oil or gas reservoirs, and unmineable coal seams) and consumption via advanced chemical and biological processes[1,2,3,4]. Presently, these options are still under investigation to determine their feasibility in terms of their storage capacity, safety, and costs.

1.2 Methods to reduce CO₂ level in atmosphere

Recent concern about increasing concentrations of CO₂ in the atmosphere has encouraged researchers to investigate various methods in order to reduce the emission of CO₂ from point source such as coal-field power plants, natural-gas burning source etc(Y.B. Melnichenko et al., 2009). Significant steps have been taken to reduce the release of CO₂ to atmosphere. However the already present CO₂ in the atmosphere is challenging. Among all the techniques carbon dioxide sequestration is the promising method for reducing the CO₂ from the atmosphere. Sequestration technique involves the adsorption mechanism to reduce the CO₂ from the atmosphere.

One way of doing this is to permanently store away the CO₂ by capturing from the atmosphere. The underground locations are the best possible sinks. However, it is much difficult to store CO₂ on somewhere on the surface. Apart from that for reducing the CO₂ level in the atmosphere the process of adsorption of CO₂ on the surface of some solid capable of acting as a physical adsorbent will be a better solution. A lot of physical adsorbents available for adsorption of CO₂ like, sandstones, sedimentary rocks in dry oil fields, deserted coalmines, off-shore outdated oil fields and deep seated coal seam are available. In this work we have concentrated upon the testing of adsorption of CO₂ on the deep Indian coal seams because coal has been found to be a potential CO₂ sink.

1.3 Coal as a geological sink

CO₂ sequestration in deep unmineable coal seams is one of the geologic strategies. Coal seam sequestration of CO₂ is particularly attractive in those cases where the CO₂ can be stored in the coal seam in an adsorbed state that is expected to be stable for geologically significant periods [5]. Injection of CO₂ may also enhance the production of the coalbed methane (CBM) to generate a profit to help offset the expense of the sequestration. If so, long-term sequestration of CO₂ in coal seams might be more cost-effective. Additionally, many power plants are located near coal seams, which would reduce the transportation costs. However, a better understanding of the chemistry of the coal- CO₂ interaction is needed in order to determine which, if any, of the coal seams might be good disposal sites and under what environmental conditions the adsorbed CO₂ would remain stable.

1.4 Problem Statement

The extent to which coal can adsorb CO₂ is affected by a number of factors. The nature of the coal will determine the maximum adsorption capacity under a given set of conditions, but the sequestration environment will determine the extent to which that ultimate capacity will be realized. The effect of both physical and chemical changes needs to be understood. Parameters such as temperature, pressure, and pH might be

expected to have a moderate to large influence; salinity might be expected to be less important.

Coal contains a wide variety of organic and mineral phases in a complex, porous, 3-dimensional Network which varies from one coal deposit to another and from one location to another within the same seam.

The organic portion of the coal is thought to capture CO₂ via surface adsorption, pore filling, and solid solution (Larsen et al. 1995). Less recognized is the possibility that the mineral phases present in the coal may assist via mineral carbonate formation. Thus, the nature of the coal seam itself is an important variable to be considered.

1.5 Objectives

- To investigate the sorption behavior of different Malaysian coal samples in presence of pure CO₂ gas.
- The second objective is to examine the sorption data to various isotherm models.
- To study the influence of various parameters such as Particle size, temperature, pressure on gas adsorption behavior.
- Recommendation of the best coal seam to be used for the project.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the background literature that is relevant to sequestration theory of carbon dioxide and important parameters affecting coal adsorption capacities based on studies done before, in addition to that it covers adsorption isotherms theory based on the IUPAC standard.

2.1 Origin and Formation of Coal

Origin, formation, and structure of coal have been studied and an enormous amount of literature is available [6, 7]. Coal is an extremely heterogeneous material consisting of organic matter, mineral matter, moisture, and a complex pore network. It is generally accepted that the organic portion of coal was formed from concentrated deposits of swampy organic matter originally derived from terrestrial plants [8]. Plant structures (leaf, stem) were converted into coal through complex biological, chemical, and geochemical processes driven initially by selective microbial action and later by the temperature and pressure generated by overlaying sediments over several hundred millions of years. The organic sedimentary rock is composed of these fossilized plant remains called macerals and mineral inclusions. The macerals are the microscopically distinct areas in coal and are mainly classified as vitrinite, liptinite, and inertinite [9]. Vitrinite is derived from woody plant material and is the most common maceral. Liptinite is formed from lipids and waxy plant substances whereas the inertinite probably originates from char formed by prehistoric pyrolysis processes, such as forest fires. The process of conversion of the plant matter into lignite, bituminous coal, and anthracite is called “coalification”. During the coalification process, large volumes of volatiles principally CH₄, CO₂, and water were liberated [10]. Although CO₂ is more strongly adsorbed to the coal matrix than the other volatiles, it is more easily dissipated because of its solubility in the water present throughout the coalification [11]. Therefore, CH₄ is the dominant gas in coal beds (about 95%) [12].

Coals are classified into ranks, which are used to define discrete points in the maturation process. Vitrinite reflectance (R%), fixed carbon content (C%), and percentage volatile matter (VM%) are used to distinguish higher-rank coals, while calorific heating value and moisture content may be used to distinguish lower-rank coals [13]. The rank system used in the United States is the American Standard Testing Method (ASTM) rank classification as shown in Figure II [13]. The ASTM classification of coal is based on the behavior of coal as a fuel rather than the carbon content of coal. The ASTM analysis is based on the volatile matter content, fixed carbon content, and the calorific value reported on a moisture- and mineral matter- free basis (mmmf).

As coal progresses through the maturation process, its physical and chemical properties change.

As the rank increases from lignite to anthracite, the carbon content increases; the oxygen content decreases; the hydrogen content decreases, slowly at first, then rapidly during the late stages of coalification; the volatile matter decreases; and the calorific value generally increases (maf basis) [13]. In addition, as rank increases, aromaticity and molecular cluster size increase; vitrinite reflectance increases; moisture content decreases, rapidly in the early stages, but slowly in the later stages of coal formation.

Rank	Group	Fixed Carbon % (mmmf)	Volatile Matter % (mmmf)	Calorific Value (mmmf) (Btu/lb)
Anthracitic	Metanthracite	>98	<2	>14,000
	Anthracite	92-98	2-8	"
	Semianthracite	86-92	8-14	"
Bituminous	Low volatile			"
	Medium Volatile	78-86	14-22	"
	High volatile A	69-78	22-31	>14,000
	High volatile B	<69	>31	13,000-14,000
	High volatile C			10,500-13,000
Subbituminous	Subbituminous A			10,500-11,500
	Subbituminous B			9,500-10,500
	Subbituminous C			8,300-9,500
Lignite	Lignite A			6,300-8,300
	Lignite B			<6,300

Standard tests:

Calorific value : measuring the heat liberated into a surrounding water jacket by burning a weighted sample of coal in a high pressure oxygen atmosphere

Moisture content : the weight loss of coal when heated to 105 °C in an inert atmosphere

Volatile matter : the weight loss of coal when heated to 950 °C in an inert atmosphere

Fixed carbon : $FC\% = 100 - (\text{moisture content}\% + \text{volatile matter}\% + \text{Ash}\%)$

Figure 2: ASTM classification of coal rank [13].

LOCATION	RESERVE			COAL TYPE
	Measured	Indicated	Inferred	
SARAWAK				
1. Silantek	7.25	10.60	32.40	Coking coal semi-anthracite, anthracite
2. Merit-Pila	176.20	107.08	121.84	Sub-bituminous
3. Bintulu	-	-	120.00	
4. Mukah-Balingan	45.60	8.30	98.10	
<i>Sub-total</i>	<i>227.05</i>	<i>125.98</i>	<i>372.34</i>	
SABAH				
1. Silimpopon	4.80	1.50	7.70	Sub-bituminous
2. Labuan	-	-	8.90	Sub-bituminous
3. Maliau	-	-	215.90	Bituminous
4. Malibau	-	17.90	25.00	
5. SW Malibau	-	26.00	-	
	<i>4.80</i>	<i>45.40</i>	<i>257.5</i>	
PENINSULAR				
1. Batu arang	-	-	17.00	Sub-bituminous
<i>Sub-total</i>			<i>17.00*</i>	
Grand Total	231.85	171.38	646.84	

Figure 3: Coal mapping locations in Malaysia [13].

2.2 Coal Proximate Analysis

The objective of coal proximate analysis is to determine the amount of fixed carbon (FC), volatile matters (VM), moisture, and ash within the coal sample. The variables are measured in weight percent (wt. %) and are calculated in several different bases. AR (as-received) basis is the most widely used basis in industrial applications. AR basis puts all variables into consideration and uses the total weight as the basis of measurement. AD (air-dried) basis neglect the presence of moistures other than inherent moisture while DB (dry-basis) leaves out all moistures, including surface moisture, inherent moisture, and other moistures. DAF (dry, ash free) basis neglect all moisture and ash constituent in coal while DMMF (dry, mineral-matter-free) basis leaves out the presence of moisture and mineral matters in coal, for example: quartz, pyrite, calcite, etc. Mineral matter is not directly measured but may be obtained by one of a number of empirical formula based on the ultimate and proximate analysis [14].

2.3 Coal Ultimate Analysis

Similar to coal proximate analysis, the objective of coal ultimate analysis is to determine the constituent of coal, but rather in a form of its basic chemical elements. The ultimate analysis determines the amount of carbon (C), hydrogen (H), oxygen (O), sulfur (S), and other elements within the coal sample. These variables are also measured in weight percent (wt. %) [14].

2.4 Gas Adsorption

When a solid is exposed to a gas or vapor, adsorption of gas onto the surfaces of the solid adsorbent occurs. Adsorption is a complicated process and different expressions are used interchangeably to define it. For instance, while the term ‘adsorption’ is used to imply the condensation of gases on free surfaces, the term ‘absorption’ or ‘imbibition’ is

used to describe the penetration of gas molecules into the mass of the absorbing solid. Likewise, the term 'sorption' is used to emphasize the adsorption on a surface, absorption by penetration into the lattice of the solid, and/or capillary condensation within the pores [15]. The IUPAC definition is generally accepted for the 'adsorption' as the enrichment of one or more components in an interfacial layer [16].

Adsorption is generally classified as chemical adsorption (chemisorption) and physical adsorption (physisorption). In chemisorption, the adsorbate becomes bound to the solid surface by a direct chemical bond. The energy generated is the same order of magnitude as the heat of reaction, which ranges between 60 and 4000 kJ/mole [17]. The surface coverage in chemisorptions is monolayer. In physisorption, the adsorption takes place mainly by van der Waals and electrostatic forces between adsorbate molecules and the atoms, which compose the adsorbent surface. Because there is no chemical bond between adsorbate molecules and the solid surface, physical adsorption is a reversible process. Physisorption is exothermic and the energy involved is not much larger than the energy of condensation of the adsorbate ranging from 8 to 40 kJ/mole [17]. It is most likely that the adsorption occurs as a monolayer at low pressures and as multilayers at relatively higher pressures depending on the type of adsorbent and the adsorbate used.

2.5 Adsorption Isotherms

The amount of gas adsorbed by a solid sample is a function of the mass of the sample, the temperature and pressure, and the nature of both the solid and the gas. The adsorption of a given gas on a particular solid can be represented by an adsorption isotherm, which is a plot of the amount adsorbed as a function of pressure at constant temperature. The shape of adsorption isotherms can provide information about the adsorption process, and the porosity as well as the surface area of the adsorbent. According to the IUPAC classification [18], there are six significantly different adsorption isotherms describing the physical adsorption as shown in Figure below [19]. A Type I isotherm generally occurs when a monolayer of adsorbate molecules is

adsorbed on a non-porous solid or when adsorption is dominated by a micropore filling process. This type of isotherm is often called a Langmuir type isotherm.

Type II is displayed by a nonporous or macroporous adsorbent. This isotherm is characterized by an inflection point, which represents the completion of the monolayer and the beginning of the formation of multilayers. Type III adsorption isotherm is typical for a non-porous or macroporous adsorbent and is observed for weak adsorbent-adsorbate interactions. Types IV isotherm, which is similar to the Type II, is typical for a mesoporous adsorbent. It displays a hysteresis loop due to capillary condensation. Type V is typical for non-porous or macroporous adsorbents and is observed for weak adsorbent-adsorbate interactions. Type VI isotherms or stepped isotherms are included in the classification although they are rare [19].

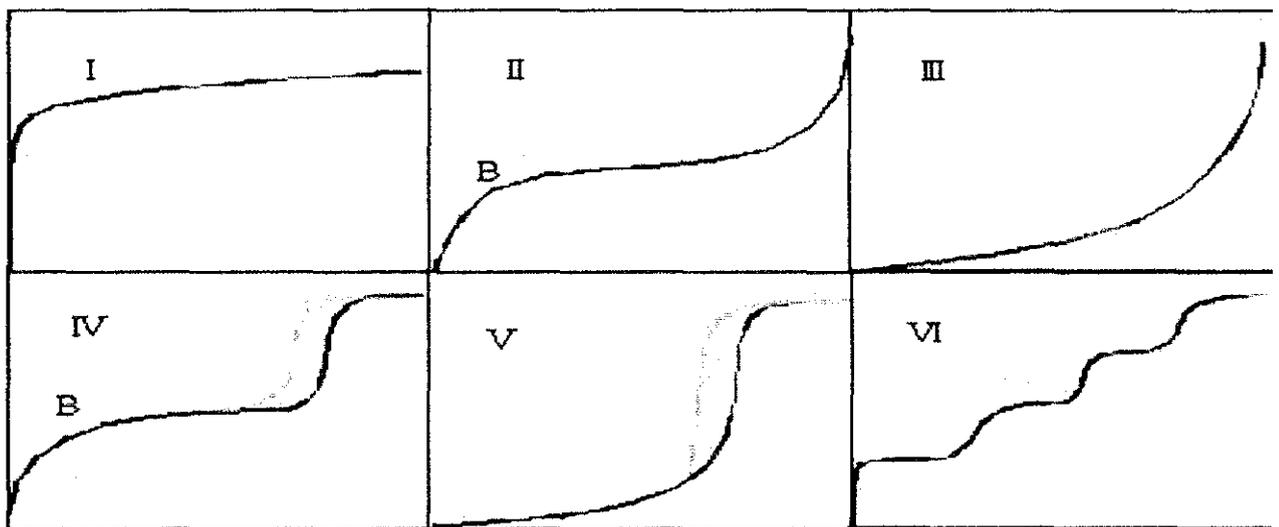


Figure 4: Types of Adsorption Isotherms

Because coal is a microporous solid, the adsorption isotherms of gases, including N₂, CH₄, and CO₂, would be expected to follow a Type I isotherm. However, various isotherms have been reported in the literature for CO₂ [20, 21].

2.6 Adsorption of Gases on Coals

A considerable literature is available on the physical adsorption of gases and vapors on microporous adsorbents, especially for activated carbon [22]. The adsorption/desorption isotherms have been studied for methane, ethane, hydrogen, and other gases as well as their binary mixtures, at elevated temperatures and pressures.

Martinez et al [22], studied the adsorption mechanisms of CO₂ in the micropores of activated anthracite with pre-adsorbed nonane.

Because n-nonane was retained within pores of different sizes, the adsorption mechanism of CO₂ could be interpreted in the narrow micropores from its adsorption isotherms. They concluded from these isotherms that the adsorption in narrow micropores with molecular dimensions is a micropore filling process, and produces a curved CO₂ isotherm. The adsorption that occurs in pores larger than two molecular diameters occurs via surface coverage and is associated with a rectilinear isotherm. Clarkson et al. applied the monolayer (Langmuir), multilayer (BET), and the potential (D-R or D-A) theories to the high-temperature, high-pressure (up to 10 MPa) CH₄ adsorption isotherms and low-pressure CO₂ isotherms in order to determine which best represented the experimental data. They found that the three-parameter D-A equation yielded the best fit to the high-pressure CH₄ isotherms. They concluded that one of the postulates of the Langmuir theory, the assumption of the energetically homogenous adsorption surface, does not apply to coal. They also concluded that, although the adsorption potential theory applies to low-pressure CO₂ isotherms, high-pressure adsorption isotherms of CO₂ needed further testing. DeGance et al. investigated pure and multicomponent adsorption isotherms of CH₄, N₂ and CO₂ on a wet coal sample under high pressures. They applied a two-dimensional equation of state, (2-D EOS), [23] the ideal adsorbed solution theory (IAS) [22], and an extended Langmuir equation to the data [24]. They concluded that although the EOS approach had some difficulty matching the experimental data for wet coals, the simplicity of the viral EOS made it useful for

modeling efforts. Chaback et al. measured the sorption isotherms of N₂, CH₄ and CO₂ on wet bituminous coals at in-situ conditions (46 C and pressures up to 11 MPa). They concluded that the Langmuir equation and its extended form satisfactorily represent the adsorption isotherms of both pure components and gas mixtures. They also showed that the relative adsorption capacities of CO₂:CH₄:N₂ are 4:2:1, respectively.

As a matter of fact, there is a good agreement between the Langmuir's monolayer and Dubinin's pore filling models. In 1972, Toda and Toyoda applied the Langmuir and Polanyi- Dubinin equations to the CO₂ on coal adsorption isotherms at 298 K. They found that there was a linear relationship between the monolayer adsorption capacity and the micropore volume as well as between the Langmuir constant, K_1 , and the inverse of the Dubinin constant, $1/K_6$. The correlation indicated that the monolayer adsorption capacity was smaller than the micropore capacity by approximately 60%.

2.6.1 Adsorption Capacity and Stability of CO₂ on Coal

Low-temperature, low-pressure adsorption of CO₂

Adsorption of CO₂ on coals has been studied extensively since 1900s, [25] however, many of these studies have been performed at low pressures (usually below atmospheric) and often low temperatures (-78°C) in order to estimate the surface area [26] and micropore structure [27] of coals. Although these low-pressure data have provided information, which is still relevant to today's sequestration projects, they do not properly represent the high pressures (up to 30 MPa) and high temperatures (up to 55 °C) environment for coal seam sequestration processes. (6) Under these conditions, CO₂ may be in gas, liquid, or supercritical phase ($T_c = 31.1$ °C and $P_c = 7.38$ MPa) depending on the change in pressure during the adsorption-desorption processes in the coal seam. Unfortunately, high-pressure, high-temperature CO₂ adsorption data on coal are limited and require additional investigation.

2.6.2 Adsorption of CO₂ under Geological Conditions

Studies of the high-pressure adsorption/desorption isotherms of CO₂ is important for determining the coals ultimate CO₂ sequestration capacity, especially under in-seam conditions. The information provided by the adsorption/desorption isotherms is used as one of the primary inputs to the simulations of coalbed sequestration processes. Such adsorption isotherms are usually obtained by one of the commonly used methods, including gravimetric, manometric (volumetric), and chromatographic [28] methods. In the gravimetric technique, the adsorption isotherms are constructed by measuring the weight change recorded by a microbalance, after accounting for the buoyancy. In the manometric technique, the adsorption isotherms are obtained by calculating the adsorbed amount of gas from an appropriate gas equation at each equilibrium pressure. In the chromatographic method, the adsorption isotherm can be obtained by frontal analysis of the breakthrough curves. It should be mentioned that the accuracy of each method strongly depends on the careful design of the measurement apparatus and experimental conditions.

Although the adsorption/desorption isotherms have been studied extensively for CH₄ and other gases at elevated temperatures and pressures, a comprehensive study of CO₂ isotherms on coals under in-situ conditions is scarce, although several studies have appeared in the literature lately [29,30]. Clarkson and Bustin studied the low- and high-pressure adsorption isotherm of CO₂ and CH₄ on four dried bituminous coals of the Cretaceous Gates Formation at pressures up to 5 MPa. They concluded that the CO₂ isotherms have a slight inflection at high-pressure, possibly as a result of multilayer adsorption. They also stated that the isotherm data are better fitted by the Dubinin-Astakhov (D-A) equation. However, coal swelling, a phenomenon that occurs when coal is contacted with adsorbing gases and vapors, was not considered and could result in such an inflection in adsorption isotherms at higher pressures.

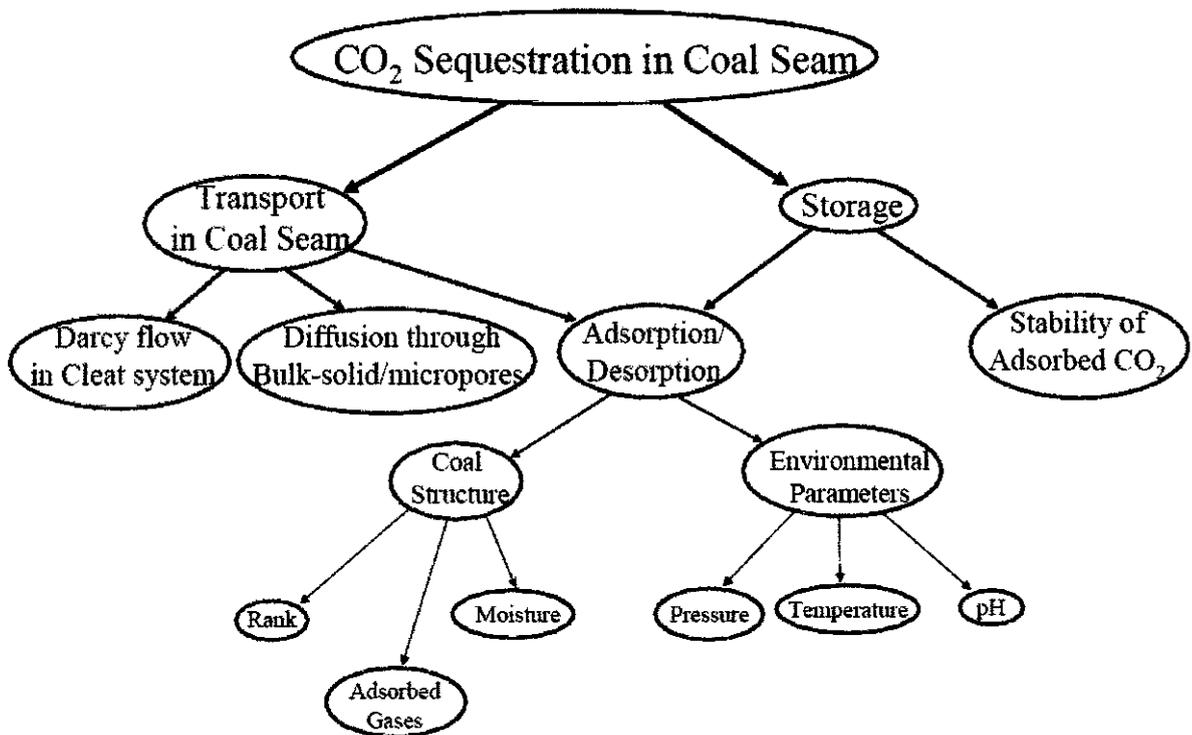


Figure 5: Areas of study of CO₂ sequestration in coal seams

2.7 Factors affecting the coal adsorption capacity and CO₂ stability

The adsorption capacity of coal and the stability of the adsorbed CO₂ can be affected by a number of factors, including those related to coal composition, i.e. rank and moisture content of the coal, and those related to the environmental variables, i.e. temperature, pressure, change in pH, and underground water floods through the coal seam. The sorption behavior of coal and the effect of temperature, moisture content, and particle size on sorption capacity have been investigated for CH₄ and comprehensive reviews are available in the literature. Here, some of the parameters that can affect the adsorption capacity and the stability of the adsorbed CO₂ are summarized:

Coal Rank: Coal contains a wide variety of organic and mineral matters in a complex, porous, three-dimensional network, which varies from one coal deposit to another and from one location to another within the same seam. The general belief is that the CH₄ adsorption capacity of coal increases with increasing coal rank. However, Bustin and Clarkson [31] have shown that there was no or little correlation between coal rank and CH₄ adsorption capacity on the coal globally although there were general trends with rank and composition in particular basins. The organic portion of the coal is thought to capture CO₂ via surface adsorption, pore filling, and solid solution [31]. Less recognized is the possibility that the mineral matters present in the coal may assist via mineral carbonate formation. Thus, the nature of the coal seam itself is an important variable to be considered in the coal seam sequestration of CO₂.

Temperature: A. S. Azmi et al., 2006, conducted the adsorption studies on the Malaysian coal samples. Their studies involved carbon dioxide adsorption profiles of coal samples of varying mean size distributions ranging from 1000 μ m to 2000 μ m. They observed that the coal samples having smaller mean particle size distribution of 1000 μ m show a better rate of adsorption compared to the 2000 μ m size distribution. These Malaysian coal samples were studied for CO₂ adsorption at varying temperatures (24.60 °C, 300 °C, 400 °C and 500 °C). The adsorption capacity of the coal sample shows an inverse response to temperature change [32]. K.Schroodre et al., 2004 conducted the adsorption test on Argonne premium coal samples using a manometric technique.

They studied the sorption characteristics at different temperatures (220°C, 300°C, 400°C, and 500°C). They observed that adsorption capacity of coal samples shows an inverse response with temperature. This is attributed to decrease in the adsorption equilibrium capacity with increasing temperature because higher temperatures increasingly favor the gas phase due to T*S entropy term in the free energy expression. Every et al., 1972, conducted experiments to find the ability of carbon dioxide, helium and air to displace methane from crushed coal. Their data showed that carbon dioxide was able to displace 90 percent methane under laboratory conditions. CO₂ was three

times more effective than air, and five times more effective than helium in displacing methane from coal.

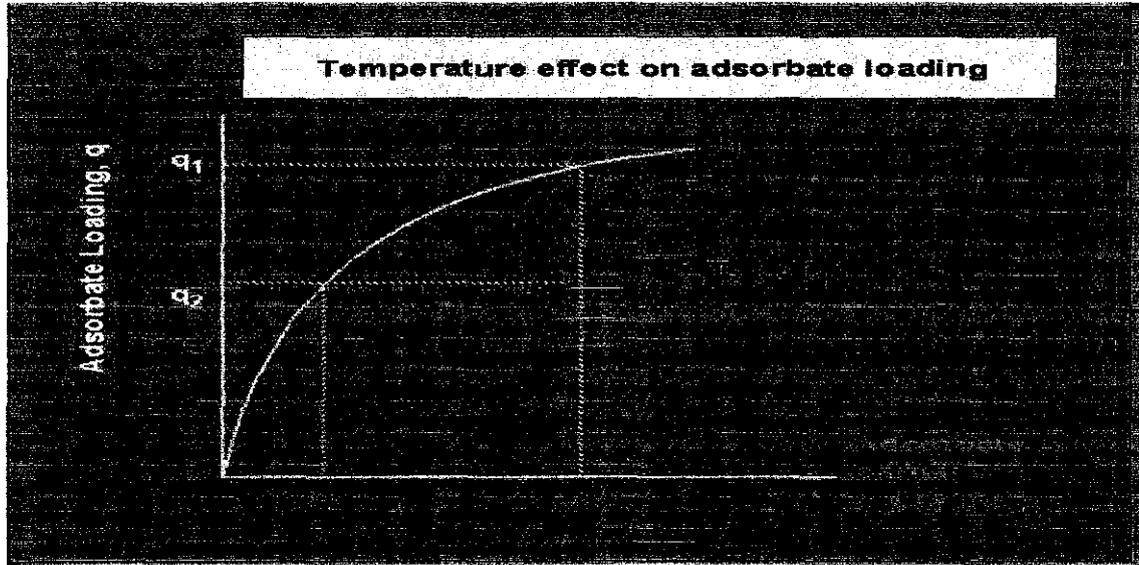


Figure 6: Pressure and Temperature effect

Moisture Content: Deep coal seams are naturally wet and will undergo recharge from surface water more rapidly during the sequestration as a result of drilling operations, fracturing of the coal bed and over-lying strata, and the injection of flue gas which may contain residual water of combustion [33]. Thus, an aqueous phase will be present and will vary in composition according to its source and the nature of the coal bed and the surrounding minerals with which it is in contact. Joubert et al [34]. Studied the effect of moisture on the sorption isotherm of CH₄ on a bituminous coal at a temperature of 30 °C and pressures up to 6.1 MPa. For all rank of coals studied, the adsorbed amount of CH₄ decreased with the moisture content up to a critical point of the coal type value.

Pre-adsorbed Components: Depending on the capture technology, the gas stream may be nearly pure CO₂, combustion gas, or something in between. Gases, such as hydrogen, methane, ethane, and higher hydrocarbons may be present in the coal seam [35] and act to inhibit or enhance the CO₂ sequestration. In the case of a gassy coal seam, it may be advantageous to displace and capture CH₄ as a profit-making part of the operation [36].

This displacement may be enhanced by secondary combustion gases, such as SO_x and NO_x. The composition of the post sequestration gas or liquid may change with time. Even slow reactions can become important over geologic-sequestration time scales. Also, microbes have an uncanny ability to adapt to many environments and are known to populate even deep geologic strata, at least to 9000 feet below the surface [37]. Under oxic conditions, gases such as SO_x, NO_x, and carbon monoxide (CO) may be produced either chemically or biologically. Under anoxic conditions, CH₄ and hydrogen sulfide (H₂S) may be produced by anaerobic microbes. These gases may displace CO₂ and thus limit the durability of the sequestration.

Coal Swelling: Coal swelling upon adsorption of gases or liquid solvents is a well-known Phenomenon. However, the adsorption capacities of coals are usually obtained by fitting the experimental data to one of the adsorption equations such as the Langmuir, Brunauer, Emmett and Teller (BET), Dubinin-Radushkevich (D-R), and Dubinin Astakhov (D-A), none of which account for the coal swelling. In order to extract valuable information from the adsorption isotherm data, it is necessary to delineate the effect of coal swelling on the adsorption isotherms and adsorption capacity of coals.

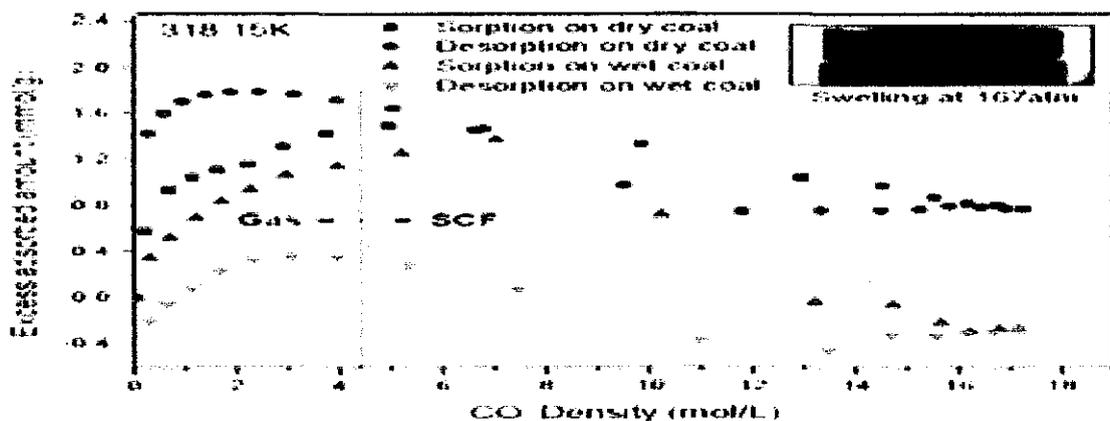


Figure 7: Some Parameters affecting Adsorption capacity [37].

CHAPTER 3

METHODOLOGY

This chapter explained the procedure of conducting the experimental of sequestrating carbon dioxide gas into a two samples of coal where the samples will be characterized and the adsorption will be conducted in bench scale equipment.

3.1 Coal samples and preparation

Two coal samples are to be arrived to UTP from different coal mines around Malaysia.

The coal samples will be crushed, grounded and sieved; these powdered samples were moisture equilibrated in an environmental chamber at the experimental temperature and 96% humidity. The moisture content of the samples was estimated using the standard test method for equilibrium [ASTM D 1424 – 93].

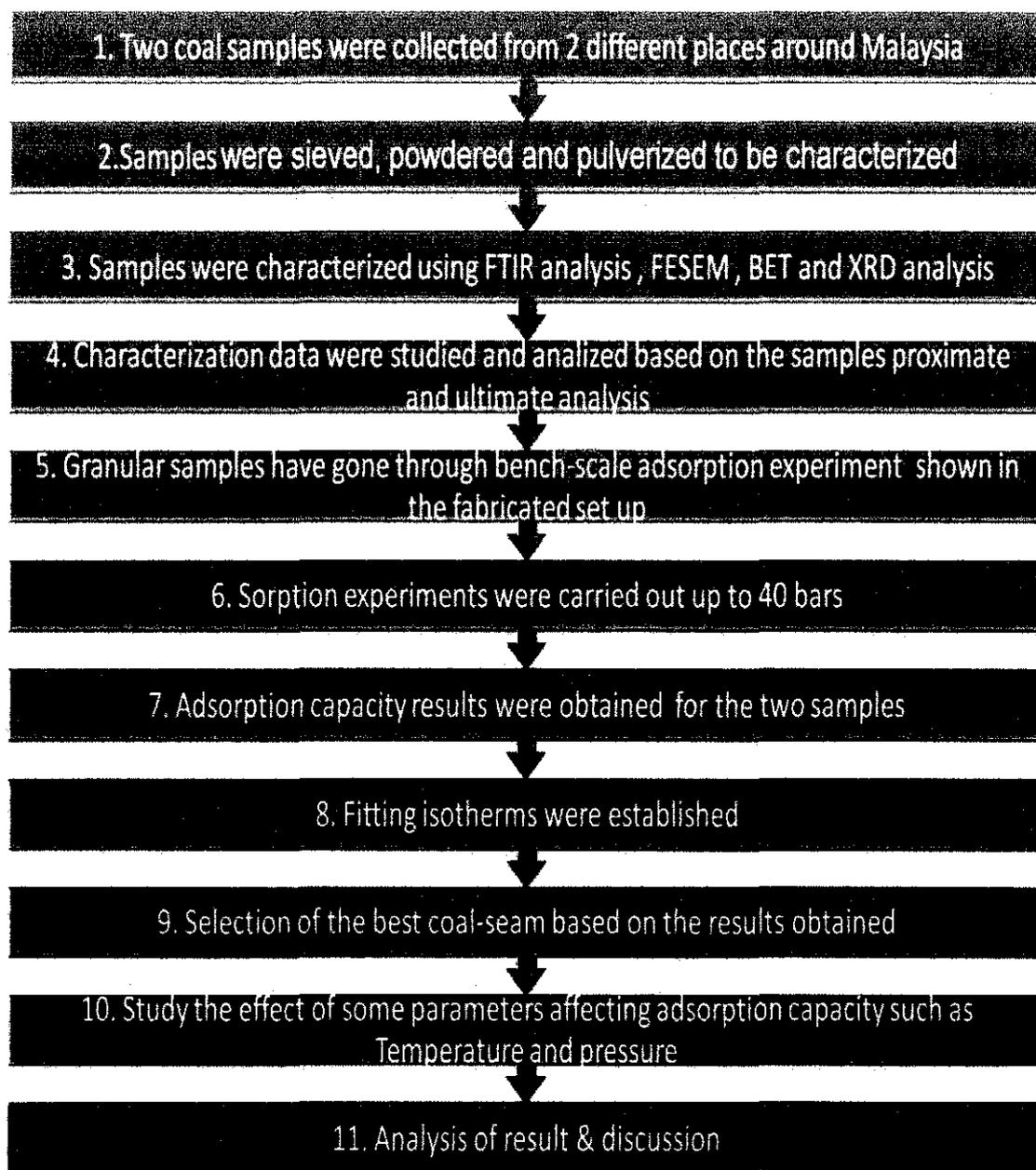
3.2 Experimentation

Samples will go for two types of experiments, where the first type is considered as sample characterization experiments where various common types of characterizations will be handled such as BET analysis, FTIR, FESEM and XRD.

The second type of experiment is the large scale or bench scale experiment where CO₂ sorption experiments were carried out in self fabricated set up which is described in the figure attached with the bench-scale experimental set up. The tests will be carried out up

to maximum pressure of 50 bars, Parameters such as temperature and inlet gas flow could be controlled along with the experiment run.

3.3 Procedure of conducting the experiment along with time



3.4 Bench scale experiment set up

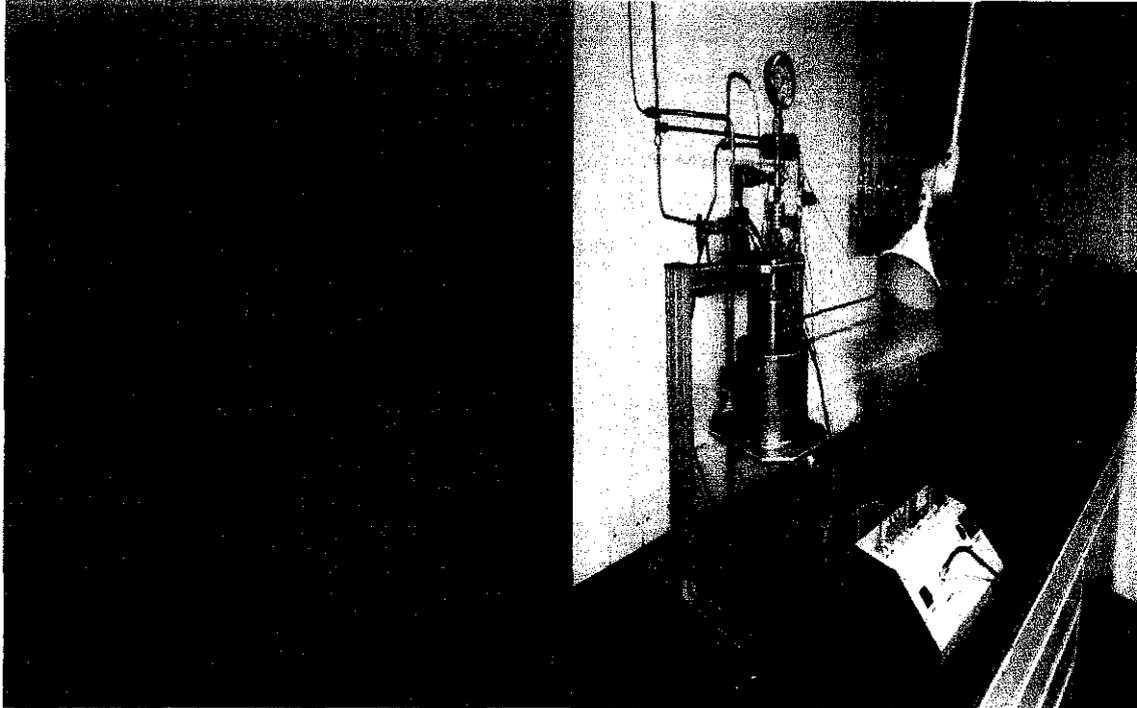


Figure 8: Equipment interface set up

Table 1: Equipment corresponding tag numbers

ID NO	Description based figure (above)
6	Reactor inside pressure, unit in barg
7	T1 temperature at near the bottom of the reactor , thermocouple K-type , unit in degree C
8	T2 temperature at near the top of reactor ,thermocouple K-type , unit in degree C
9	T3 temperature at near the middle of reactor ,thermocouple K-type , unit in degree C

10	Gas inlet temperature to reactor , thermocouple K-type ,unit in degree C
11	Gas outlet temperature to reactor, thermocouple K-type, unit in degree C
12	Gas inlet flow rate set value button (SV) , unit in ml/minute
13	Gas inlet actual flow rate , process value (PV)
14	Gas Outlet flow rate set value button (SV) ,unit in ml/minute
15	Gas Outlet actual flow rate , process value (PV)
16	Press “Record” button to start the recording function
17	Press “Print” button to export the data to Excel file
18	Press “Reset” button to reset the data logging to zero
19	Data logging table

High pressure feed gas is brought into a contact with the adsorbent at different operating parameters where the adsorbent packed column is synchronized with the control system and automation system. Parameters such as temperature, pressure and the inlet gas flow can be controlled through this equipment and results can be obtained from the computer attached with the equipment. The sweet gas which is already adsorbed is then sent to a gas chromatography device where some important data will be captured such as the gas outlet composition and after difference of the inlet feed gas and the outlet sweet gas will be the amount adsorbed which will be directly plotted versus the operating sets of pressure of the bed in order to determine the corresponding adsorption isotherm which suits the coal case.

CHAPTER 4

RESULT AND DISCUSSION

This chapter shows the results that being obtained through experimental characterization and the bench scale equipment as well, the adsorption isotherms obtained are plotted across with fixing the temperature parameters at 25 C.

Samples characterization results

4.1 Sample Characterization

Two coal samples were collected from two different mines in Malaysia, where one is located in Sungai Buloh and the other one is located in Silantek Sarawak, the sample were sieved, powdered and pulverized in order to be prepared for the characterization where the samples are to go through FTIR analysis, XRD analysis, FESEM analysis and finally BET surface area and pore size analysis.

4.2 FTIR Analysis

Fourier transform infrared (FTIR) spectroscopy is an analysis technique that provides information regarding the molecular structure and chemical bonding of materials. These materials can be organic or inorganic. FTIR is used primarily in failure analysis (scientific process of collecting data for determining the cause of a particular failure) in order to identify unknown materials.

The FTIR technique operates on the fact that chemical bonds and groups of chemical bonds of molecules vibrate at certain (characteristic) frequencies. In particular, molecules that are exposed to infrared rays absorb those rays at frequencies that are unique to those molecules, according to SiliconFarEast.com. The analysis can be

performed on gases, liquids and solids. As a result, FTIR spectroscopy is a very useful technique in identifying unknown components of a mixture.

Samples combined observations

FTIR coal spectra is shown and optimized. In assigning the bands, the absorption bands are compared with the standard patterns (Grigoriev 1990; Karr 1978; Scheinman 1970; Speight 1994; Cooke *et al* 1986; Das 2001). Adsorption chain is observed at 3400 cm^{-1} and 3423 cm^{-1} in the coal samples, which appears to be mainly due to N–H and O–H groups. FT-IR spectra of the samples further show that O–H stretching vibrations are situated at 3853, 3752, 3622 and 3412 cm^{-1} . The peaks for O–H groups at 3600–3800 cm^{-1} appear to be for those associated with clay minerals. The aromatic hydrogen band at 3040 cm^{-1} is absent in the coal indicating its highly substituted and condensed nature. The peak at 2918 cm^{-1} and 2850 cm^{-1} appearing as sharp peaks of medium intensity, may be assigned to aliphatic and alicyclic CH₃, CH₂ and CH groups although the major contribution is expected to be due to CH₂ groups. The intensity of peaks at 2920 cm^{-1} and 2928.43 cm^{-1} are greater than the peak 2850 cm^{-1} indicating the presence of long aliphatic chains in the coal. The peak at 1699 cm^{-1} appears to indicate the presence of carbonyl (C=O) content. The peak around 1600 cm^{-1} in the coal is observed due to aromatic C=C, vinylic C=C and possibly due to other O-containing functional groups. The oxygen containing functional groups found in coal specifically include phenols and alcohols, ethers, carboxylic acid and carbonyls. In view of the diversity of decomposed plant matter, finding any systematic variation in the distribution of these functional groups in coal seems unlikely. Several authors have reviewed quantitative determination of these various oxygen functional groups. A strong band at 1436 cm^{-1} in the coal was observed. This is mainly due to CH₃ asymmetric deformation and CH₂ group in bridges but may also be partly due to aromatic C=C and strongly hydrogen bonded O–H groups. The band at 1372 cm^{-1} is mainly due to CH₃ symmetric deformation while –CH₃ and –CH₂ in cyclic structures may also partly

contribute to this band. Intensity of this peak is much lower than the peak at regions 1436 cm^{-1} and 1458.6 cm^{-1} indicating that the methylene as long side chains. The band between 880 cm^{-1} , 750 cm^{-1} and 722.6 cm^{-1} has been assigned to aromatic structures. The weak band at 690 cm^{-1} observed in the coal could possibly be due to C-S bond. These absorptions are most useful in determining the aromatic ring structure of a coal.

Concluding all affected function group, it's highly noticed that if the peak transmittance intensity has lower values, then the corresponding chain composition exists more in the coal sample, and vice versa.

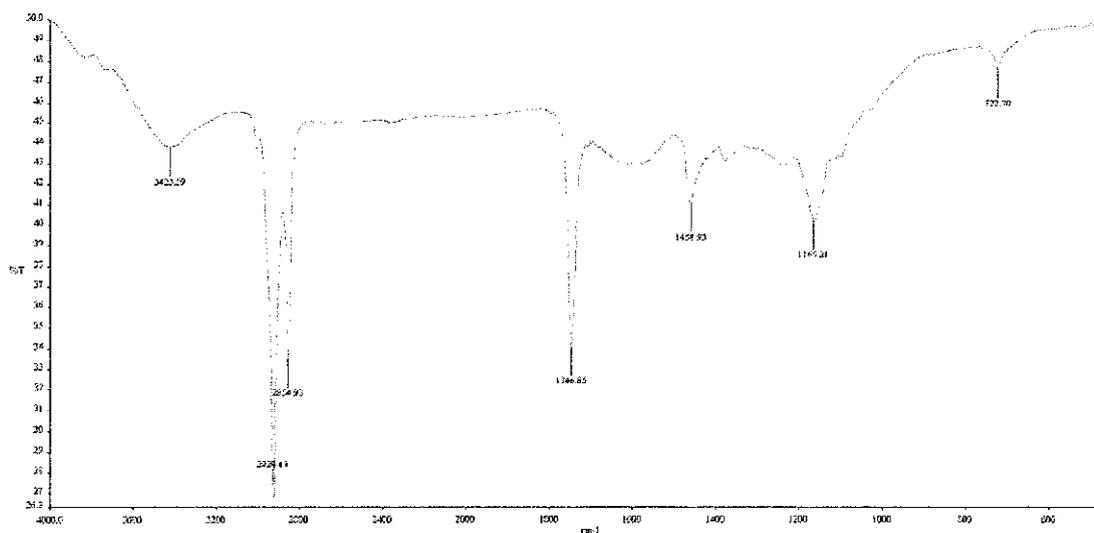


Figure 9: Sungai Buloh coal sample FTIR analysis

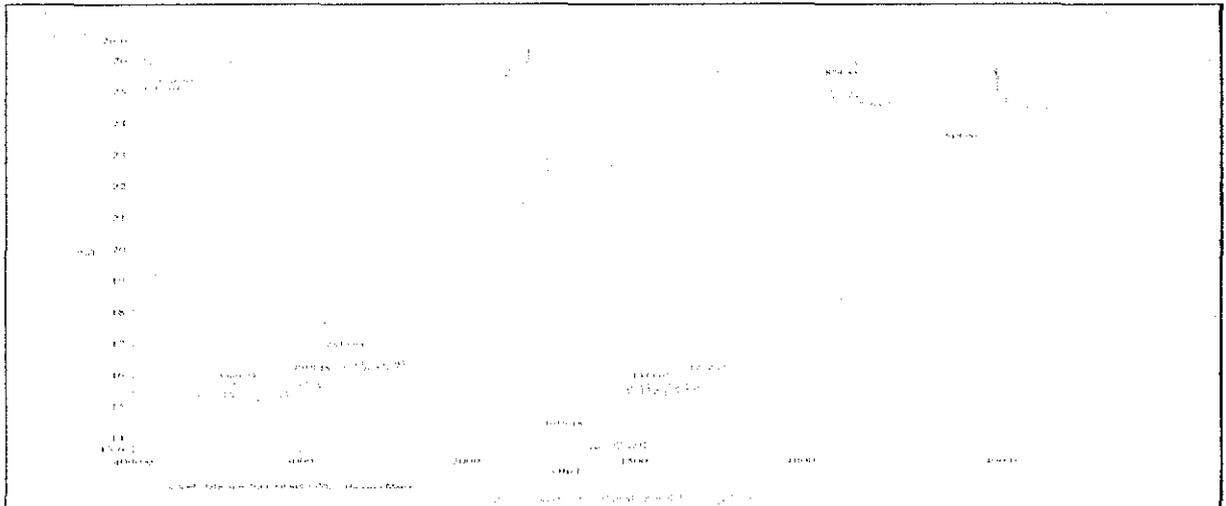


Figure 10: Silantek coal sample FTIR analysis

Concluding all affected function group, it's highly noticed that if the peak transmittance intensity has lower values, then the corresponding chain composition exists more in the coal sample, and vice versa.

4.3 XRD Analysis

Sample data were analyzed and optimized where a bulky coal sample is prepared for XRD without heating shows that the data of peaks produced in peak list were investigated through the data cards and arrived at the conclusion that the sample contained pyrite, kaolinite and minor presence of hematite. In addition it was highly observed that the sample did not contain quartz.

Two bulky coal samples have gone through different procedure where the sample was heated at 500 °C for ½ hour in oxidizing atmosphere and the XRD Graph of the heated sample as presented in figure below was obtained. The comparative examination of peaks on XRD graphs (unheated and heated) was made through the recorded peak lists. The peaks corresponding to pyrite in unheated sample appeared as the peaks of hematite in heated sample. The unaffected hematite appeared in both the unheated sample as well as in the heated sample. The peaks 9 of kaolinite however, did not appear in the XRD pattern of heated sample. It is presumed that the kaolinite would have changed into

amorphous form on heating that is why the kaolinite peak did not appear in the XRD graph.

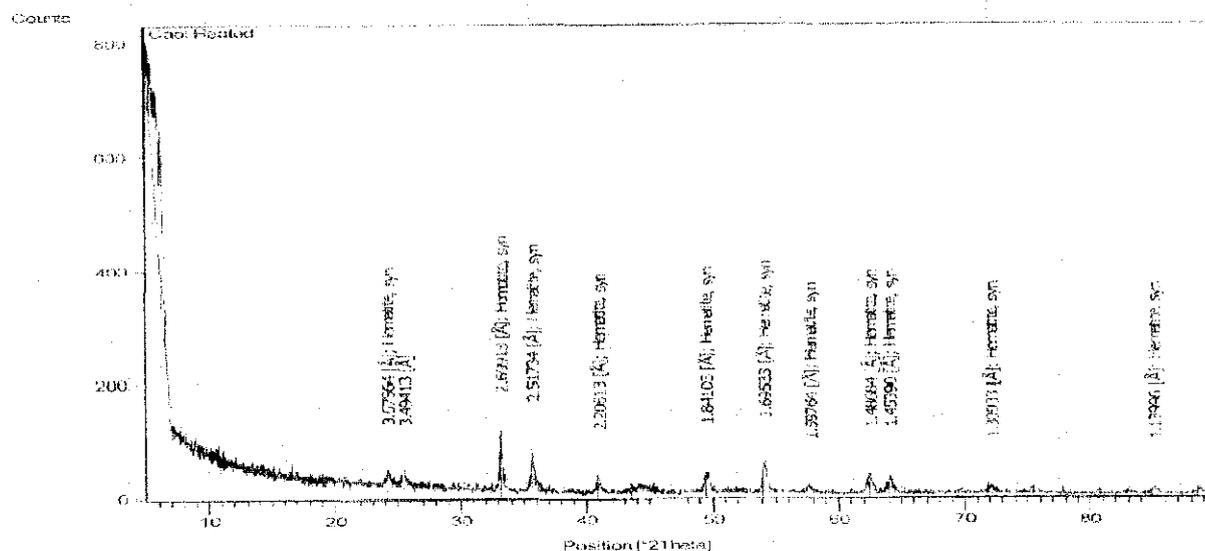


Figure 11: XRD graph of a bulk coal sample heated up till 500 °C

4.4 FESEM Principle

a field-emission cathode in the electron gun of a scanning electron microscope provides narrower probing beams at low as well as high electron energy, resulting in both improved spatial resolution and minimized sample charging and damage. Under vacuum, electrons generated by a Field Emission Source are accelerated in a field gradient. The beam passes through Electromagnetic Lenses, focusing onto the specimen.

As result of this bombardment different types of electrons are emitted from the specimen. A detector catches the secondary electrons and an image of the sample surface is constructed by comparing the intensity of these secondary electrons to the scanning primary electron beam. Finally the image is displayed on a monitor.

The FE-SEM is equipped with EDX Energy Dispersive X-Ray (EDX) spectroscopy system with a take-off angle for quantitative analysis, digital imaging, and X-ray mapping. EDAX Phoenix microanalysis system contains the EDAM III data acquisition module, which allows for flexibility and enhanced performance through Digital Signal Processing for spectral and image acquisition and data reduction where all the results obtained are shown in the figures below.

Table 2: Samples EDX analysis

Element	Weight%	Atomic%	Element	Weight%	Atomic%
C K	59.18	67.17	C K	64.58	79.86
O K	35.72	30.43	O K	28.18	17.12
Al K	3.19	1.61	Al K	3.19	1.13
Si K	0.97	0.47	Si K	4.05	1.90
Ca K	0.94	0.32			
Totals	100.00		Totals	100.00	

Silantek sample EDX analysis

Sungai sample EDX analysis

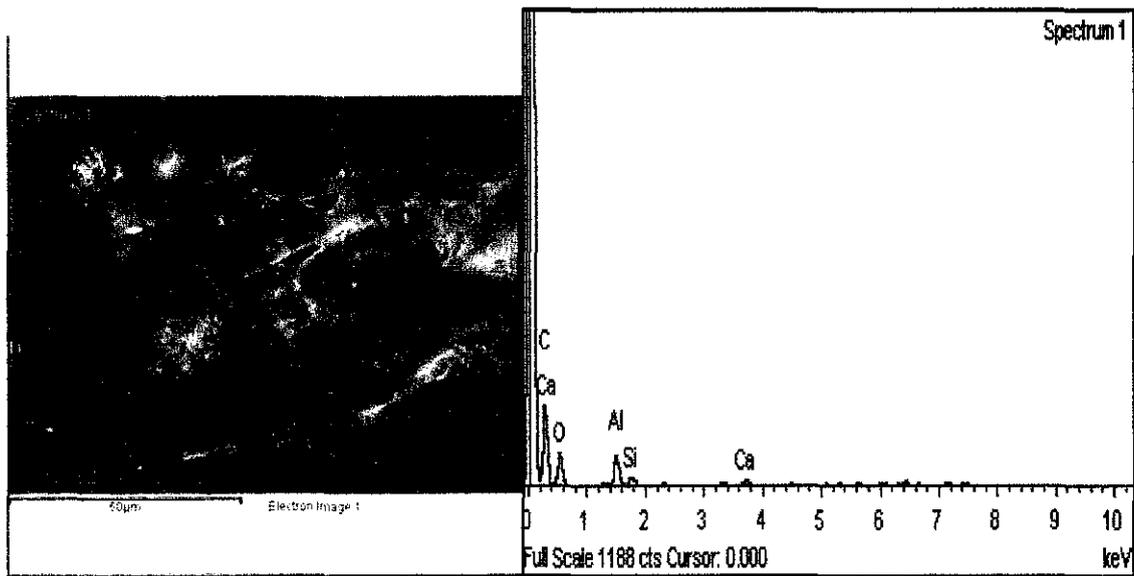


Figure 12: EDX analysis of a sample bulk mixture

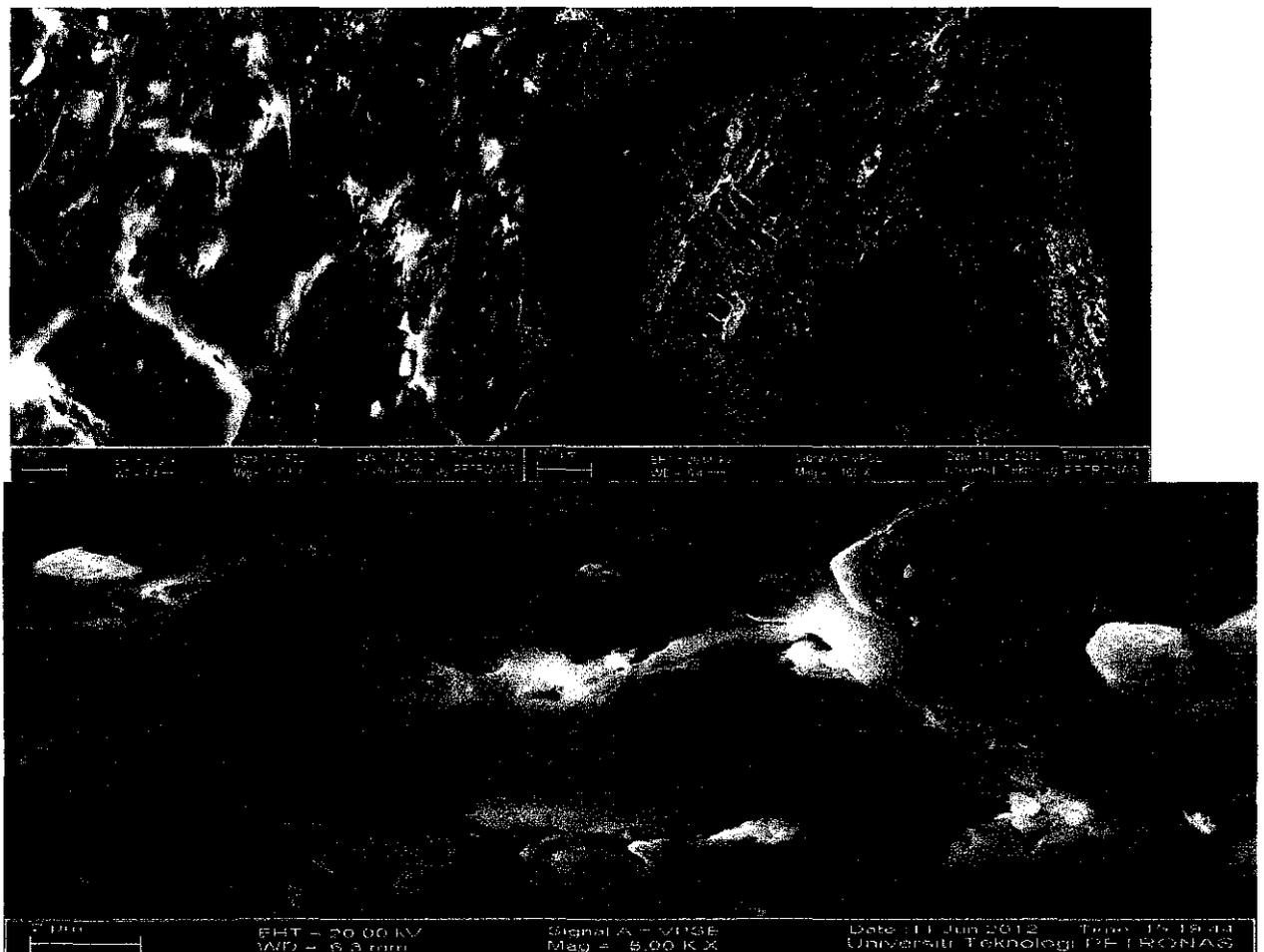


Figure 13: FESEM images of the two samples taken at different resolutions

4.5 BET Surface Area & Gas Adsorption

BET surface area analysis is a technique used to determine the specific surface area of powders, solids and granules, the values are expressed in meter square per gram.

Clean solid surfaces adsorb surrounding gas molecules and Brunauer, Emmett and Teller theory (BET) provides a mathematical model for the process of gas sorption. This physical adsorption of a gas over the entire exposed surface of a material and the filling of pores is called physisorption and is used to measure total surface area and pore size analysis of nanopores, micropores and mesopores.

The BET surface area measurement is crucial in understanding the behaviour of a material, as material reacts with its surroundings via its surface, a higher surface area material is more likely to react faster, dissolve faster and adsorb more gas than a similar material with a lower surface area.

BET Summary Report for Sungai Buloh sample

Surface Area

BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å
width: 1.495 m²/g

BJH Desorption cumulative surface area of pores between 17.000 Å and 3000.000 Å
width: 2.7078 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 1342.026 Å width at P/P₀ =
0.985364386: 0.003409 cm³/g

Single point desorption total pore volume of pores less than 1095.032 Å width at P/Po = 0.981995509: 0.003395 cm³/g

BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å width: 0.014720 cm³/g

BJH Desorption cumulative volume of pores between 17.000 Å and 3000.000 Å width: 0.014311 cm³/g

Pore Size

BJH Adsorption average pore width (4V/A): 393.938 Å

BJH Desorption average pore width (4V/A): 211.407 Å

BET Summary Report for Silantek sample

Surface Area

BJH Adsorption cumulative surface area of pores between 17.000 Å and 3000.000 Å width: 0.013 m²/g

Pore Volume

Single point adsorption total pore volume of pores less than 1157.026 Å width at P/Po = 0.982978226: 0.000036 cm³/g

BJH Adsorption cumulative volume of pores between 17.000 Å and 3000.000 Å width: 0.000477 cm³/g

Pore Size

BJH Adsorption average pore width (4V/A): 1433.481 Å

From the results obtained above we observed that that Sungai Buloh coal sample has much more better results than Silantek sample, which was noticed in the BET isotherm graph.

Actually there are some parameters affecting coal adsorption of nitrogen as it's not favorable that is due to the degassing temperature of coal which is not specified yet leading to accumulation of a moisture particles occupying the pores affecting the capacity as it was noticed strongly in the Silantek sample where the BET isotherm against N₂ gas was tested various times and that was the most convenient result obtained.

4.6 Geochemistry

Carbon dioxide estimation on coal samples were done on dry ash free basis.

Characteristics of coal are an important parameter that dictates the sorption potential of coal. The proximate and ultimate analysis results are depicted in Table below.

Table 3: Proximate and ultimate analysis

Coals	Silantek	Sungai Buloh
Calorific Value(Kcal/Kg)	5800	5030
Proximate Analysis (%)		
Moisture	14.6	15.3
Volatile matter	36.5	38.8
Fixed Carbon	44.5	37.9
Ash	4.4	8.2
Ultimate Analysis (%)		
Carbon	59.18	56.23
Hydrogen	6.4	5.2
Nitrogen	1.1	1.3
Sulfur	0	0

From the results obtained above it was observed that the ash content in the silantek coal sample is ranked low, and that is due to the coal type properties as it's considered as sub-anthracite coal.

Unlike the sample obtained from Sarawak region, it was shown that it has high ash content as it is also considered a sub-bituminous coal type.

Prior to that , there is no much difference between the amount of fixed carbon of the two types which has a great influence in the adsorption capacity and the isotherms which will be obtained In general it is recognized that the fixed carbon of coal increases with increase in coal depth.

Bench-scale equipment results

4.7 Adsorption Capacity

The adsorption capacity of CO₂ on coal samples was determined using above described apparatus and procedure described in the previous section. The sorption capacity of some results obtained is shown below , where we observe that by increasing the operating gas pressure , the amount adsorbed by the coal samples will be more with respect to the temperature variable which was set to be fixed at room temperature along with the experiment run.

Table 4: Amount adsorbed at corresponding pressure

Pressure(bar)	Amount ads(mmol/gads)	
	Silantek	Sungai Buloh
0	0	0
5	1.0708333	0.417
10	2.238	0.832666667
20	4.0041667	2.025833333
25	4.056275	2.5875
30	4.1725	3.273333333
40	4.1783333	3.635166667

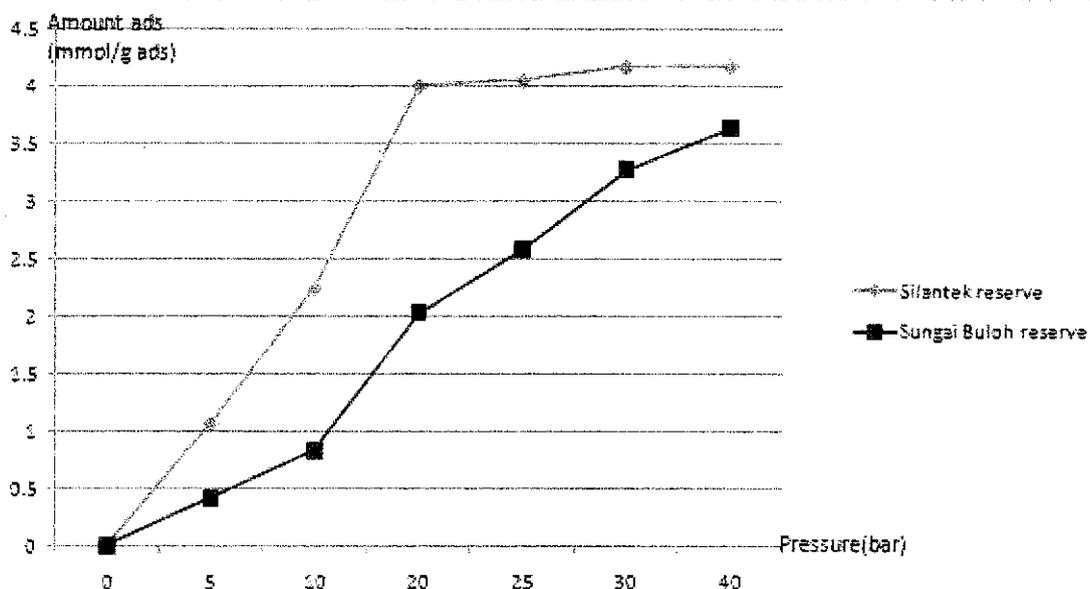


Figure 14: Adsorption behavior of the two samples obtained at 25 °C

From the figure described above, it was observed that Silantek sample gives higher sorption capacity 4.18 mmol/g ads followed by Sungai Buloh sample which has a sorption capacity of 3.64 mmol/g ads.

Silantek sample exhibited higher sorption capacity due to variety of coal composition structure as it has a higher amount of fixed carbons and low ash content unlike the other sample which has a higher ash and moisture content and it has lower amount of fixed carbons.

Adsorption behavior of the two samples is following type 1 isotherm compared to the six types of IUPAC standard isotherms, and the reason goes back to the theory where coal is considered a microporous solid.

4.8 Effect of temperature on the adsorption capacity of the samples

Temperature is a crucial parameter in adsorption reactions. According to the adsorption theory, adsorption decreases with increase in temperature and molecules adsorbed earlier on a surface tend to desorb from the surface at elevated temperatures.

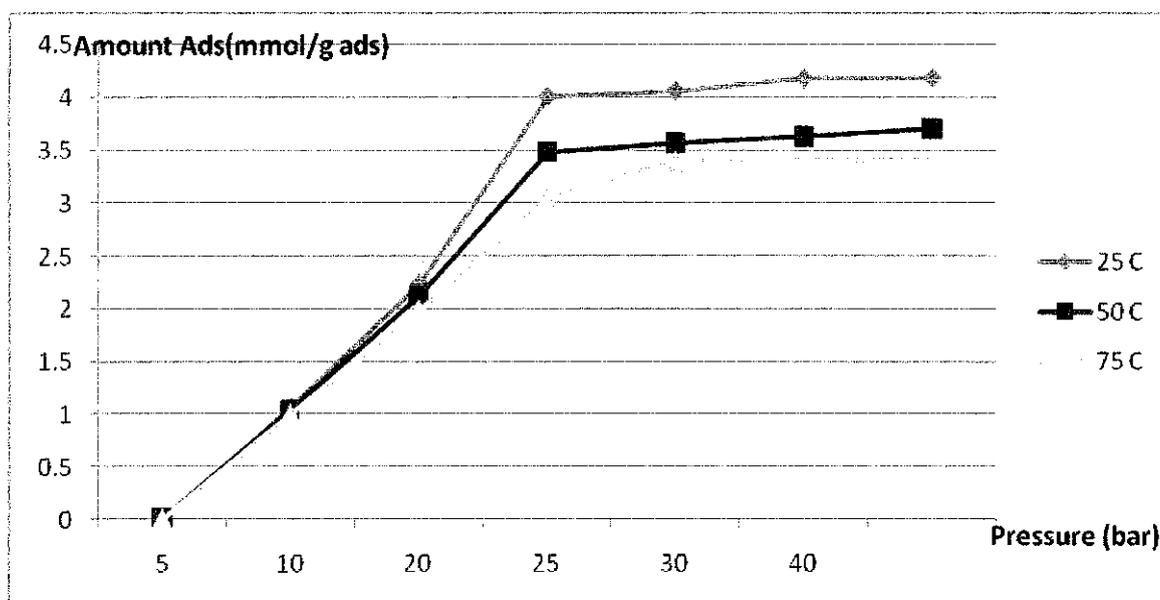


Figure 15: Effect of Temperature on Silantek sample

From the results obtained, the silantek sample difference in temperature between 25 C and 75 C has almost 20% losses in the adsorption capacity of the specified coal samples.

In addition to that the adsorption capacity of the silantek sample is highly recommended at higher pressure as the physical monolayer surface adsorption of coal favors high pressure and that was proved based on the results obtained.

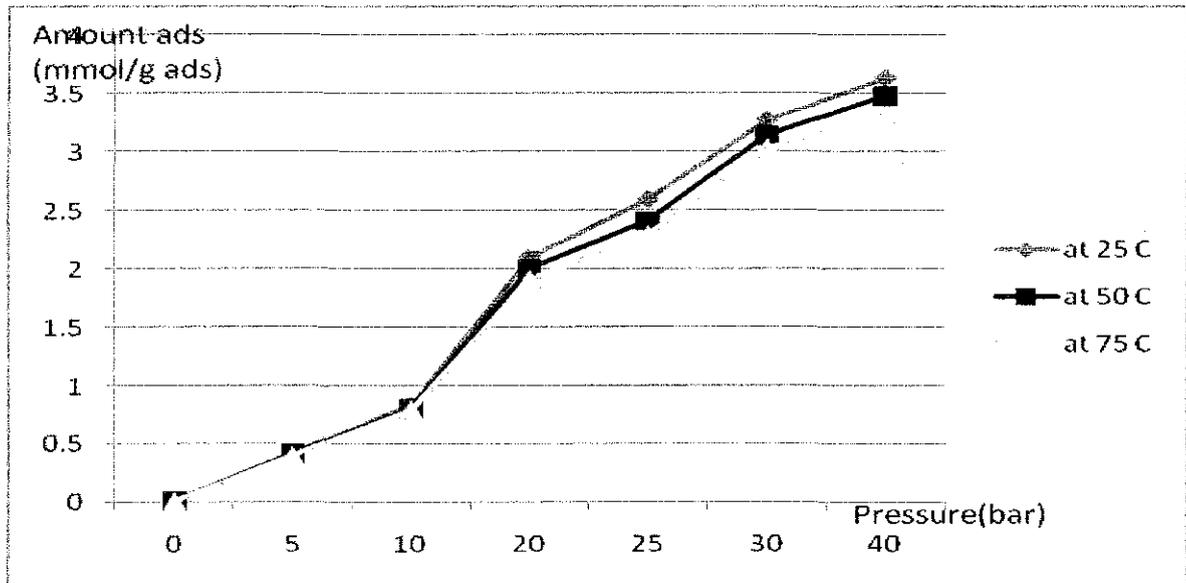


Figure 16: Effect of Temperature on Sungai Buloh sample

Similar to Silantek sample the difference in temperature between 25 °C and 75 °C experimental trials is almost 10% in the adsorption capacity of the specified coal sample.

Moreover, the adsorption capacity of the Sungai Buloh sample is highly recommended at higher pressures.

The main reason goes to the complex structure of Sungai Buloh sample, as specified earlier that the sample has high ash and moisture content which directly related to the poor adsorption performance obtained by the sample.

4.9 Adsorption isotherm models

Various isotherms for adsorption of gases on solids have been analyzed using different approaches such as Langmuir theory, Freundlich theory, and Temkin approach.

The corresponding equation parameters were calculated using linear regression analysis of the experimental data and the corresponding related isotherm parameters were described in the table below, where the isotherms were plotted at 25 °C.

Table 5: Isotherms corresponding parameters

Samples collected	Langmuir Parameters		Freundlich Parameters		Temkin Parameters		Amount Co ₂ Adsorbed (mmol/g)
	K	q ₀	K	n	b	A	
Silantek sample	-0.771	-2.01	1.159	9.346	40021.25	6.536	4.178
Sungai Buloh sample	-6.882	-58.8	0.366	5.319	35697.789	0.676	3.635

4.9.1 Longmuir adsorption Isotherm

Whenever a gas is in contact with a solid there will be an equilibrium established between the molecules in the gasphase and the corresponding adsorbed species (molecules or atoms) which are bound to the surface of the solid.

The basic idea behind the Langmuir model is the coverage of the surface by a monomolecular layer. The model approach also assumes that only one gas is being adsorbed. Thus, at constant temperature a part of the surface will be covered with the adsorbed molecule another part not.

Between the free gas and the adsorbed gas a dynamic equilibrium will exist. Per time unit there will be as much molecules adsorbing as there will be desorbing. The rate of adsorption will be proportional with the equilibrium pressure of the gas and the free surface.

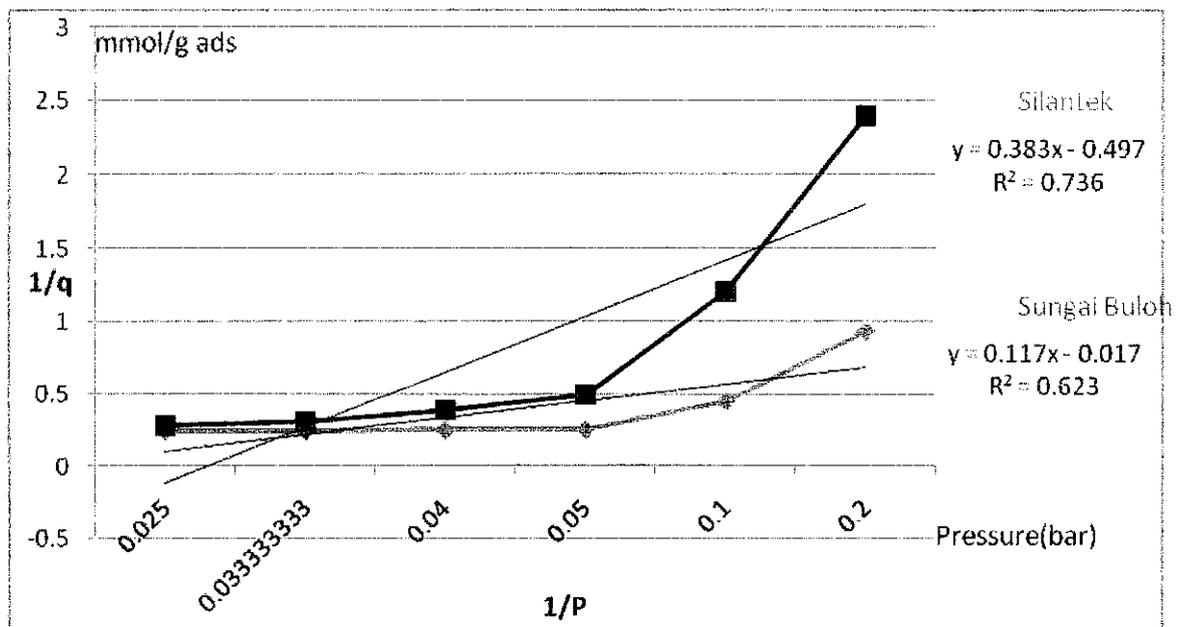


Figure 17: Longmuir adsorption isotherm obtained at 25 C

Coal is able to store a significant amount of gas. The mechanism by which this occurs is called adsorption. In adsorption molecules of one substance become attached to the surface of another. Adsorption can be visualized by imagining a magnet attached to a metal surface, or lint attached to a sweater. This is different from absorption where one substance becomes trapped inside another, such as a sponge soaking up water. Adsorption is a reversible process, because that involves weak attraction forces.

The Langmuir adsorption isotherm assumes that the gas attaches to the surface of the coal and covers the surface as a single layer of gas (a monolayer). Nearly all of the gas stored by adsorption coal exists in a condensed, near liquid state. At low pressures, this dense state allows greater volumes to be stored by sorption than is possible by compression.

Langmuir isotherm failed to describe the adsorption behavior of both samples; therefore more isotherms are applied to obtain the most convenient isotherm describing the adsorption behavior.

4.9.2 Freundlich adsorption Isotherm

Freundlich expressed an empirical equation for representing the isothermal variation of adsorption of a quantity of gas adsorbed by unit mass of solid adsorbent with pressure.

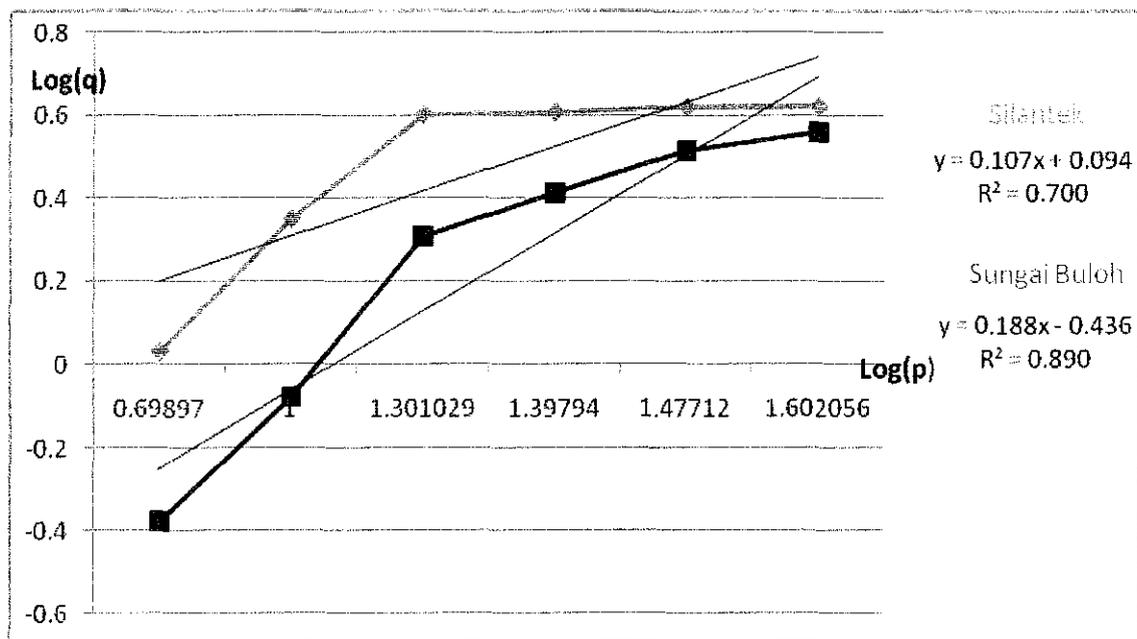


Figure 18: Freundlich isotherm obtained at 25 °C

Experimentally it was determined that extent of adsorption varies directly with pressure till saturation pressure P_s is reached. Beyond that point rate of adsorption saturates even after applying higher pressure. Thus Freundlich Adsorption Isotherm is almost perfect at higher pressures based on the results data obtained.

Freundlich isotherm has better behavior for Sungai Buloh sample based on the line regression values.

4.9.3 Temkin adsorption Isotherm

Temkin's isotherm contains a factor that explicitly takes into account the adsorbent adsorbate interactions. The heat of adsorption of all the molecules in the layer would decrease linearly with coverage due to adsorbent-adsorbate interactions. The adsorption is characterized by a uniform distribution of binding energies, up to some maximum binding energy.

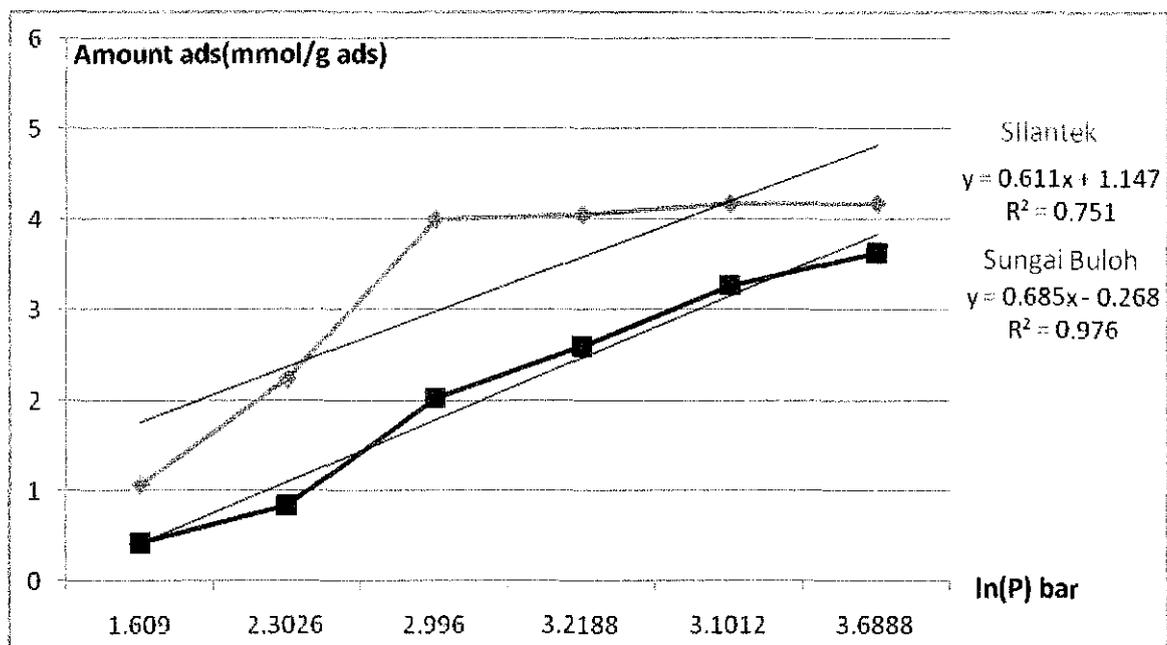


Figure 19: Temkin Isotherm described for both samples at 25 °C

Temkin adsorption isotherm was found to be the most convenient isotherm to describe the adsorption behavior of the carbon dioxide gas into both coal samples based on the line regression data.

The deviation noticed in the first two points has a vital explanation whereby the time when the experiment starts for lower pressure the built up pressure is quite fast, therefore it's quite hard to control the reactor's start up gas pressure inlet to the reactor, but when the time passes the gas inlet pressure is remained constant and that's what the results proved.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Sequestration of carbon dioxide is an important way to get rid of carbon dioxide gas emissions to the atmosphere, as it was found that the coal is capable of storing the green house gas for long periods rather than the other techniques endorsed.

An experimental and theoretical study has been conducted to obtain the adsorption capacity of coals and parameters that affect the coal- CO₂ interactions. An experimental setup was constructed to measure the adsorption isotherms of CO₂ two different coal samples one is collected from Sungai Buloh mine and the other one is collected from Silantek mine.

Sequestration of carbon dioxide in the coal seams is highly favorable at high pressure injection gas rate and low temperature.

Among the two samples Silantek sample has higher adsorption capacity of 4.178 mmol/g at corresponding pressure of 40 bars.

For both samples a fitting isotherm is plotted and the Temkin adsorption isotherm was the most convenient isotherm obtained by the data based on the line regression values provided with the graphs.

Samples adsorptions are following type I in the IUPAC standard where the Longmuir isotherm is failed to describe the adsorption behavior of the carbon dioxide into coal.

5.2 Recommendation

The experiment had been conducted for a batch process only. To obtain more similar to the process industry, the test should be done in a continuous process together with other equipment such as valves, pumps and others. In addition to that a pressure controller should be introduced on the high pressure gas line, so that we can eliminate the pressure built up while running the experiment and also the feed gas to the bed will be steadier.

Furthermore, the temperature controller should act faster and take further response where sometimes we have to wait a lot for the temperature to raise up or to cool down.

Moreover, the inlet gas line should be controlled automatically for higher flow rate of the carbon dioxide gas inlet to the bed, as that will make it easier for the one running the experiment.

Finally, UTP should provide sensors to detect any leakage of the gas, as we are dealing with a very high pressure on the industrial scale and that will cause fatal problems if it's not taken seriously.

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CHAPTER 6: APPENDIX

6.1 GANTT CHART AND KEY MILESTONES

Gantt charts for activities planned along for this final year projects first and second semester are shown in Table 11 and Table 12.

Table 6: Gantt chart for final year project first semester (FYP I)

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	
1	Selection of Project Topic								Mid-Semester Break								
2	Preliminary Research Work																
3	Submission of Extended Proposal						●										
4	Oral Proposal Defence										●						
5	Project Work Continues																
6	Submission of Interim Draft Report															●	
7	Submission of Finalized Interim Report																●

Table 7: Gantt chart for final year project second semester (FYP II)

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	
1	Project Work Continues								Mid-Semester Break									
2	Submission of Progress Report									●								
3	Project Work Continues																	
4	Pre-EDX													●				
5	Submission of Draft Report													●				
6	Submission of Dissertation (soft bound)															●		
7	Submission of Technical Paper															●		
8	Oral Presentation																●	
9	Submission of Project Dissertation (hard bound)																	●

6.2 Experimental data

Silantek sample trial at operating pressure of 10 bars and 25 C corresponding temperature.

Time	Gas In Temp/'C	Gas Out Temp/'C	T1/'C	T2/'C	T3/'C	Pressure/Bar	MFC1/mg/min	MFC2mg/min
20	19.9	0	20.2	20.2	23.3	0	0	0
40	19.7	0	20.2	20	23.3	0	0.4	0
60	19.7	0	20.3	20.1	23.5	0	600	0
80	20.1	0	20.8	20.6	23.9	0.1	599.8	0
100	20.4	0	21.4	21.1	24.5	0.1	599.6	0
120	20.7	0	21.8	21.4	25.1	0.2	599.9	0
140	20.9	0	22.4	21.9	25.6	0.3	600.9	0
160	21.3	0	22.8	22.4	26.3	0.4	599.7	0
180	21.2	0	23.2	22.5	26.8	0.4	600	0
200	21.4	0	23.7	22.8	27.4	0.5	600.1	0
220	21.3	0	24	23	27.8	0.6	598.1	0
240	21.3	0	24.3	23.2	28.6	0.7	600	0
260	21.4	0	25	23.5	28.7	0.8	600.2	0
280	21.7	0	25.6	23.9	29.4	0.8	600.2	0
300	21.8	0	26	24.3	29.6	0.9	600.2	0
320	21.9	0	26.6	24.6	30.3	1	599.9	0
340	22.2	0	27.2	24.8	30.6	1.1	600	0
360	22.3	0	27.7	25.2	31.1	1.2	600.1	0
380	22.4	0	28.5	25.3	31.4	1.3	600.1	0
400	22.6	0	29	25.6	31.7	1.4	600.3	0
420	22.7	0	29.6	25.9	32.1	1.5	600.4	0
440	22.8	0	30.1	26.1	32.4	1.6	599.8	0
460	23	0	30.7	26.3	32.7	1.7	600.8	0
480	23	0	31.3	26.5	33.3	1.9	600.3	0
500.2	22.9	0	31.5	26.5	33.5	2	600.5	0
520.2	23	0	32	26.7	33.7	2.1	600.1	0
540.2	23	0	32.4	26.7	34.1	2.2	600.7	0
560.2	23	0	32.7	26.8	34.4	2.4	600.4	0
580.2	23	0	33.1	27.1	34.7	2.5	600.3	0
600.2	23	0	33.5	26.9	34.8	2.6	605.4	0
620.2	22.8	0	33.7	26.9	35	2.8	600.2	0
640.2	23	0	34.3	27.2	35.3	2.9	600.2	0
660.2	23	0	34.5	27.2	35.4	3	600.9	0

680.2	23	0	34.9	27.6	35.6	3.2	600.9	0
700.2	23.1	0	35.2	27.6	35.9	3.3	600.1	0
720.2	23	0	35.5	27.7	35.9	3.5	599.7	0
740.2	23.3	0	36	28	36.2	3.6	600.4	0
760.2	23.3	0	36.3	28.1	36.3	3.8	600.5	0
780.2	23.3	0	36.4	28.1	36.6	3.9	600.5	0
800.2	23.5	0	36.8	28.5	36.7	4.1	600.3	0
820.2	23.5	0	37.2	28.6	36.8	4.3	599.7	0
840.2	23.5	0	37.2	28.6	36.9	4.4	600.9	0
860.2	23.6	0	37.6	28.8	37.1	4.6	600.4	0
880.2	23.7	0	37.9	28.9	37.2	4.8	600.3	0
900.2	23.6	0	37.9	28.9	37.4	5	600.7	0
920.2	23.6	0	38	28.9	37.5	5.1	600.2	0
940.2	23.6	0	38.1	28.9	37.6	5.3	599.9	0
960.2	23.5	0	38.1	28.8	37.8	5.5	600.4	0
980.2	23.6	0	38.3	28.9	37.9	5.7	600.1	0
1000.2	23.8	0	38.6	29	38.1	5.9	600.7	0
1020.2	23.7	0	38.6	28.9	38.1	6.1	600.4	0
1040.2	23.7	0	38.6	29.3	38.1	6.3	600.1	0
1060.2	23.8	0	38.7	29.2	38.4	6.5	600.3	0
1080.2	23.8	0	38.8	29.3	38.4	6.7	600.2	0
1100.2	23.8	0	38.9	29.4	38.5	6.9	600.3	0
1120.2	23.9	0	38.9	29.4	38.7	7.1	600.9	0
1140.2	24	0	39.1	29.5	38.7	7.3	600.4	0
1160.2	24	0	38.9	29.5	38.7	7.5	600.7	0
1180.2	24	0	39.3	29.6	38.7	7.7	600.5	0
1200.2	24	0	39.1	29.5	38.8	8	599.8	0
1220.2	24	0	38.9	29.3	38.8	8.2	600.4	0
1240.2	23.8	0	38.9	29.4	39	8.4	600.8	0
1260.2	23.9	0	38.8	29.5	39	8.6	600.2	0
1280.2	24	0	38.8	29.5	39	8.8	600.2	0
1300.2	23.9	0	38.5	29.4	39	9.1	600.2	0
1320.2	23.9	0	38.5	29.4	39	9.3	600.5	0
1340.2	23.8	0	38.5	29.5	39	9.5	600	0
1360.2	23.7	0	38.1	29.2	39.1	9.8	600.2	0
1380.2	23.7	0	38.1	29.3	39.1	10	599.3	0
1400.2	23.7	0	38.1	29.4	39.1	10.3	598.3	0
1420.2	23.6	0	37.7	29.3	39.1	10.3	0	0
1440.2	23.6	0	37.4	29.2	39	10.3	0	0
1460.2	23.5	0	37.1	29	39	10.2	0	0
1480.2	23.7	0	36.9	29.2	38.7	10.2	0	0
1500.2	23.6	0	36.8	29.3	38.7	10.1	0	0
1520.2	23.6	0	36.3	28.9	38.4	10.1	0	0
1540.2	23.6	0	36.1	29.5	38.4	10	0	0
1560.2	23.6	0	35.7	28.9	38.1	10	0	0
1580.2	23.6	0	35.4	28.9	37.9	10	0	0
1600.2	23.7	0	35.2	28.8	37.6	9.9	0	0
1620.2	23.6	0	34.9	28.7	37.3	9.9	0	0

1640.2	23.6	0	34.6	28.8	37.2	9.8	0	0
1660.2	23.7	0	34.4	28.8	37	9.8	0	0
1680.2	23.6	0	34.1	28.6	36.9	9.8	0	0
1700.2	23.6	0	33.9	28.6	36.8	9.7	0	0
1720.2	23.6	0	33.8	28.6	36.4	9.7	0	0
1740.2	23.6	0	33.5	28.6	36.1	9.7	0	0
1760.2	23.7	0	33.2	28.6	35.8	9.6	0	0
1780.2	23.6	0	33.1	28.4	35.8	9.6	0	0
1800.2	23.6	0	32.8	28.4	35.5	9.6	0	0
1820.2	23.7	0	32.7	28.5	35.2	9.6	0	0
1840.2	23.7	0	32.4	28.4	35.2	9.6	0	0
1860.2	23.7	0	32.3	28.4	34.9	9.5	0	0
1880.2	23.7	0	32.3	28.4	34.9	9.5	0	0
1900.2	23.7	0	31.9	28.2	34.8	9.5	0	0
1920.2	23.6	0	31.7	28	34.8	9.4	0	0
1940.2	23.7	0	31.5	28.1	34.6	9.4	0	0
1960.2	23.7	0	31.4	28	34.3	9.4	0	0
1980.2	23.7	0	31.2	27.9	34.2	9.4	0	0
2000.2	23.7	0	31	27.9	34	9.4	0	0
2020.2	23.6	0	30.9	27.8	33.7	9.3	0	0
2040.2	23.5	0	30.6	27.7	33.7	9.3	0	0
2060.2	23.6	0	30.5	27.7	33.6	9.3	0	0
2080.2	23.6	0	30.5	27.7	33.4	9.3	0	0
2100.2	23.5	0	30.3	27.6	33.3	9.3	0	0
2120.2	23.6	0	30.3	27.6	33.1	9.2	0	0
2140.2	23.6	0	30.1	27.5	33	9.2	0	0
2160.2	23.5	0	30	27.5	33	9.2	0	0
2180.2	23.6	0	29.8	27.5	32.7	9.2	0	0
2200.2	23.6	0	29.6	27.3	32.7	9.2	0	0
2220.2	23.6	0	29.7	27.2	32.7	9.1	0	0
2240.2	23.5	0	29.5	27.2	32.4	9.1	0	0
2260.2	23.6	0	29.4	27.2	32.3	9.1	0	0
2280.2	23.6	0	29.3	27.1	32.2	9.1	0	0
2300.2	23.6	0	29.3	27	32.1	9.1	0	0
2320.2	23.6	0	29.3	27.1	32.1	9.1	0	0
2340.2	23.6	0	29	27.1	31.8	9.1	0	0
2360.2	23.6	0	28.9	27	31.8	9	0	0
2380.2	23.5	0	28.9	26.8	31.6	9	0	0
2400.2	23.7	0	28.9	27	31.6	9	0	0
2420.2	23.8	0	28.7	26.9	31.3	9	0	0
2440.2	23.7	0	28.7	26.9	31.3	9	0	0
2460.2	23.8	0	28.7	26.8	31.3	9	0	0
2480.2	23.7	0	28.5	26.8	31.2	9	0	0
2500.2	23.8	0	28.4	26.8	30.9	8.9	0	0
2520.2	23.7	0	28.5	26.8	30.8	8.9	0	0
2540.2	23.7	0	28.2	26.7	30.9	8.9	0	0
2560.2	23.8	0	28.2	26.7	30.5	8.9	0	0
2580.2	23.7	0	28.2	26.7	30.5	8.9	0	0

2600.2	23.7	0	28.1	26.7	30.5	8.9	0	0
2620.2	23.7	0	28	26.7	30.6	8.9	0	0
2640.2	23.8	0	28	26.7	30.6	8.9	0	0
2660.2	23.7	0	27.9	26.6	30.4	8.9	0	0
2680.2	23.7	0	28	26.5	30.1	8.9	0	0
2700.2	23.7	0	27.8	26.6	30.1	8.8	0	0
2720.2	23.7	0	27.7	26.5	30.1	8.8	0	0
2740.2	23.7	0	27.8	26.5	30	8.8	0	0
2760.2	23.7	0	27.6	26.4	29.8	8.8	0	0
2780.2	23.7	0	27.6	26.4	29.8	8.8	0	0
2800.2	23.8	0	27.5	26.3	29.5	8.8	0	0
2820.2	23.7	0	27.6	26.3	29.5	8.8	0	0
2840.2	23.7	0	27.3	26.3	29.5	8.8	0	0
2860.2	23.8	0	27.2	26.3	29.5	8.8	0	0
2880.2	23.7	0	27.2	26.3	29.5	8.7	0	0
2900.2	23.8	0	27.2	26.2	29.5	8.7	0	0
2920.2	23.7	0	27.2	26.2	29.5	8.7	0	0
2940.2	23.8	0	27.1	26.2	29.2	8.7	0	0
2960.2	23.7	0	27	26.1	29.2	8.7	0	0
2980.2	23.7	0	27	26.2	29.2	8.7	0	0
3000.2	23.7	0	26.9	26.1	29.1	8.7	0	0
3020.2	23.7	0	26.9	26.2	29.1	8.7	0	0
3040.2	23.7	0	26.9	26	28.9	8.7	0	0
3060.2	23.7	0	26.8	26.1	28.9	8.7	0	0
3080.2	23.7	0	26.8	26.1	28.8	8.7	0	0
3100.2	23.7	0	26.8	26	28.9	8.7	0	0
3120.2	23.8	0	26.7	26	28.8	8.6	0	0
3140.2	23.6	0	26.7	25.9	28.6	8.6	0	0
3160.2	23.6	0	26.7	26	28.6	8.6	0	0
3180.2	23.6	0	26.7	25.9	28.4	8.6	0	0
3200.2	23.6	0	26.6	25.9	28.4	8.6	0	0
3220.2	23.6	0	26.6	25.8	28.5	8.6	0	0
3240.2	23.6	0	26.6	25.8	28.5	8.6	0	0
3260.2	23.6	0	26.6	25.9	28.5	8.6	0	0
3280.2	23.6	0	26.5	25.7	28.5	8.6	0	0
3300.2	23.7	0	26.4	25.7	28.3	8.6	0	0
3320.2	23.6	0	26.5	25.8	28.3	8.6	0	0
3340.2	23.6	0	26.3	25.7	28.2	8.6	0	0
3360.2	23.7	0	26.5	25.8	28.2	8.5	0	0
3380.2	23.6	0	26.4	25.7	28	8.5	0	0
3400.2	23.7	0	26.4	25.6	28	8.5	0	0
3420.2	23.7	0	26.5	25.7	27.7	8.5	0	0
3440.2	23.7	0	26.3	25.7	28	8.5	0	0
3460.2	23.7	0	26.3	25.8	28	8.5	0	0
3480.2	23.7	0	26.4	25.8	27.9	8.5	0	0
3500.2	23.7	0	26.4	25.8	27.7	8.5	0	0
3520.2	23.8	0	26.4	25.8	27.7	8.5	0	0
3540.2	23.8	0	26.3	25.8	27.5	8.5	0	0

3560.2	23.8	0	26.2	25.7	27.6	8.5	0	0
3580.2	23.8	0	26.3	25.6	27.5	8.5	0	0
3600.2	23.8	0	26.3	25.6	27.6	8.5	0	0
3620.2	23.7	0	26.2	25.6	27.6	8.5	0	0
3640.2	23.7	0	26.2	25.6	27.5	8.5	0	0
3660.2	23.6	0	26.1	25.6	27.4	8.5	0	0
3680.2	23.7	0	26.1	25.6	27.4	8.5	0	0
3700.2	23.6	0	26.1	25.5	27.4	8.5	0	0
3720.2	23.7	0	26	25.5	27.3	8.4	0	0
3740.2	23.5	0	26	25.5	27.3	8.4	0	0
3760.2	23.6	0	26	25.4	27.3	8.5	0	0
3780.2	23.5	0	25.9	25.2	27.2	8.4	0	0
3800.2	23.5	0	25.9	25.4	27.2	8.4	0	0

Sungai Buloh sample trial at operating pressure of 10 bars and 25 C corresponding temperature.

<i>Time</i>	<i>Gas In Temp/°C</i>	<i>Gas Out Temp/°C</i>	<i>T1/°C</i>	<i>T2/°C</i>	<i>T3/°C</i>	<i>Pressure/Bar</i>	<i>MFC1/mg/min</i>	<i>MFC2mg/min</i>
20	19.8	0	25.5	26.3	30.9	0	499.6	0
40	20.1	0	25.7	26.9	31.2	0.4	587.4	0
60.1	20	0	25.9	27	31.7	0.7	598.4	0
80.1	19.9	0	26.2	27.1	31.8	1	597.2	0
100.1	20	0	26.6	27.3	32.4	1.2	600.2	0
120.1	20.4	0	27.3	28	32.9	1.5	600.5	0
140.1	20.6	0	28.4	28.4	33.3	1.8	596.4	0
160.1	20.8	0	29	28.8	33.7	2.1	596.2	0
180.1	20.9	0	29.8	29	34.1	2.4	598.8	0
200.1	21.1	0	30.6	29.5	34.7	2.7	601.2	0
220.1	21.3	0	31.4	29.8	34.9	3	600.6	0
240.1	21.5	0	32.1	30.1	35.3	3.2	600.9	0
260.1	21.3	0	32.7	30.2	35.7	3.5	600.9	0
280.1	21.3	0	33.2	30.4	36.2	3.9	601.3	0
300.1	21.5	0	33.7	30.4	36.6	4.2	600.2	0
320.1	21.6	0	34.5	30.6	36.9	4.5	600.4	0
340.1	21.8	0	35.1	30.7	37.2	4.8	597.3	0
360.1	21.9	0	35.6	31.1	37.4	4.9	38.7	0
380.1	22	0	36.3	31.1	37.8	4.8	23.1	0
400.1	22.2	0	36.9	31.8	37.9	5.8	598.5	0
420.1	22.4	0	37.8	32	38.1	6.1	599.9	0
440.1	22.4	0	38.1	32	38.4	6.4	600.1	0
460.1	22.4	0	38.6	32.1	38.7	6.7	600.2	0
480.1	22.4	0	38.8	32.1	38.8	7	600.7	0
500.1	22.4	0	39.6	32.3	39	7.3	600.2	0
520.1	22.5	0	39.9	32.6	39	7.6	601.9	0
540.1	22.7	0	40.4	32.8	39.1	7.8	593.7	0
560.1	22.7	0	40.8	32.8	39.2	8.1	600.5	0
580.1	22.9	0	41.2	33	39.4	8.4	599.3	0
600.1	22.9	0	41.8	33.1	39.6	8.7	602	0
620.1	22.9	0	42	33.5	39.6	9	601.5	0
640.1	23	0	42.4	33.6	39.6	9.4	601	0
660.1	23.1	0	42.9	33.6	39.6	9.7	600	0
680.1	23.1	0	43	33.8	39.6	10	600.1	0
700.1	23.2	0	43.5	33.9	39.6	10.2	0	0
720.1	23.2	0	43.7	33.7	39.6	10.1	0	0
740.1	23.2	0	43.8	33.6	39.6	10	0	0
760.1	23.3	0	44	33.6	39.4	10	0	0
780.1	23.2	0	44	33.6	39.4	9.9	0	0
800.1	23.1	0	44.1	33.3	39.3	9.9	0	0
820.1	23	0	44.1	33.3	39.1	9.8	0	0

840.1	23.1	0	44.2	33.2	39.1	9.8	0	0
860.1	23.1	0	44.4	33.2	39	9.8	0	0
880.1	23.1	0	44.4	33.2	39	9.7	0	0
900.1	23	0	44.4	33	39	9.7	0	0
920.1	23.1	0	44.5	33.1	39	9.6	0	0
940.1	23.1	0	44.6	33.1	38.7	9.6	0	0
960.1	23.1	0	44.6	33.1	38.7	9.6	0	0
980.1	23.1	0	44.7	33.1	38.7	9.5	0	0
1000.1	23.1	0	44.5	33	38.7	9.5	0	0
1020.1	23.2	0	44.5	33	38.7	9.5	0	0
1040.1	23	0	44.6	33	38.5	9.4	0	0
1060.1	23.2	0	44.6	33.1	38.5	9.4	0	0
1080.1	23.1	0	44.6	33.1	38.4	9.4	0	0
1100.1	23.1	0	44.5	33.1	38.7	9.4	0	0
1120.1	23	0	44.5	33	38.4	9.4	0	0
1140.1	23.2	0	44.5	33	38.4	9.3	0	0
1160.1	23.3	0	44.5	33.2	38.2	9.3	0	0
1180.1	23.3	0	44.6	33.1	38.2	9.3	0	0
1200.1	23.4	0	44.6	33.2	38.1	9.2	0	0
1220.1	23.3	0	44.5	33.2	38.1	9.2	0	0
1240.1	23.4	0	44.6	33.1	38.1	9.2	0	0
1260.1	23.3	0	44.5	33.1	38.1	9.2	0	0
1280.1	23.4	0	44.5	33.1	38	9.2	0	0
1300.1	23.2	0	44.5	33.1	37.9	9.1	0	0
1320.1	23.4	0	44.5	33.3	37.9	9.1	0	0
1340.1	23.2	0	44.2	33	37.9	9.1	0	0
1360.1	23.2	0	44.2	33	38	9.1	0	0
1380.1	23.2	0	44.1	32.9	37.9	9	0	0
1400.1	23.4	0	44.2	33	37.9	9	0	0
1420.1	23.4	0	44.1	33.1	37.8	9	0	0
1440.1	23.4	0	44	33	37.6	9	0	0
1460.1	23.2	0	44	32.9	37.6	9	0	0
1480.1	23.3	0	44	33	37.6	9	0	0
1500.1	23.4	0	43.9	32.9	37.6	8.9	0	0
1520.1	23.1	0	43.8	32.9	37.5	8.9	0	0
1540.1	23.3	0	43.9	32.9	37.6	8.9	0	0
1560.1	23.3	0	43.8	32.8	37.5	8.9	0	0
1580.1	23.2	0	43.8	32.8	37.6	8.9	0	0
1600.1	23.3	0	43.7	32.9	37.4	8.9	0	0
1620.1	23.3	0	43.6	32.9	37.5	8.8	0	0
1640.1	23.4	0	43.7	32.9	37.4	8.8	0	0
1660.1	23.4	0	43.6	32.9	37.4	8.8	0	0
1680.1	23.5	0	43.6	32.9	37.5	8.8	0	0
1700.1	23.4	0	43.5	32.9	37.4	8.8	0	0
1720.1	23.3	0	43.5	32.8	37.3	8.8	0	0
1740.1	23.5	0	43.5	32.9	37.3	8.7	0	0
1760.1	23.4	0	43.5	32.8	37.3	8.7	0	0
1780.1	23.4	0	43.3	32.8	37.3	8.7	0	0

1800.1	23.4	0	43.3	32.7	37.2	8.7	0	0
1820.1	23.5	0	43.3	32.7	37.2	8.7	0	0
1840.1	23.3	0	43.2	32.7	37.2	8.7	0	0
1860.1	23.5	0	43.2	32.8	37.2	8.7	0	0
1880.1	23.5	0	43	32.8	37.2	8.6	0	0
1900.1	23.4	0	43.1	32.8	37.2	8.6	0	0
1920.1	23.5	0	43.1	32.7	37.2	8.6	0	0
1940.1	23.4	0	43	32.7	37.2	8.6	0	0
1960.1	23.3	0	43	32.7	37	8.6	0	0
1980.1	23.4	0	42.9	32.8	37	8.6	0	0
2000.1	23.5	0	42.8	32.7	36.9	8.6	0	0
2020.1	23.4	0	42.9	32.7	36.8	8.5	0	0
2040.1	23.5	0	42.7	32.8	36.8	8.5	0	0
2060.1	23.5	0	42.7	32.6	36.8	8.5	0	0
2080.1	23.5	0	42.5	32.7	36.9	8.5	0	0
2100.1	23.5	0	42.5	32.6	36.8	8.5	0	0
2120.1	23.5	0	42.5	32.4	36.9	8.5	0	0
2140.1	23.5	0	42.5	32.7	36.9	8.5	0	0
2160.1	23.5	0	42.4	32.6	36.8	8.5	0	0
2180.1	23.5	0	42.4	32.6	36.9	8.4	0	0
2200.1	23.5	0	42.3	32.4	36.9	8.4	0	0
2220.1	23.5	0	42.2	32.4	36.8	8.4	0	0
2240.1	23.5	0	42.2	32.4	36.7	8.4	0	0
2260.1	23.5	0	42.1	32.3	36.7	8.4	0	0
2280.1	23.4	0	42	32.3	36.7	8.4	0	0
2300.1	23.4	0	42	32.4	36.7	8.4	0	0
2320.1	23.4	0	42	32.2	36.7	8.4	0	0
2340.1	23.5	0	41.9	32.3	36.7	8.4	0	0
2360.1	23.5	0	41.9	32.2	36.7	8.4	0	0
2380.1	23.4	0	41.9	32.2	36.5	8.3	0	0
2400.1	23.5	0	41.8	32.3	36.7	8.3	0	0
2420.1	23.5	0	41.6	32.2	36.7	8.3	0	0
2440.1	23.5	0	41.6	32.3	36.7	8.3	0	0
2460.1	23.5	0	41.6	32.1	36.5	8.3	0	0
2480.1	23.5	0	41.5	32.2	36.5	8.3	0	0
2500.1	23.5	0	41.5	32	36.6	8.3	0	0
2520.1	23.4	0	41.4	32.2	36.4	8.3	0	0
2540.1	23.4	0	41.5	32.1	36.4	8.3	0	0
2560.1	23.5	0	41.3	32.1	36.4	8.3	0	0
2580.1	23.5	0	41.2	32.1	36.4	8.2	0	0
2600.1	23.5	0	41.1	32	36.4	8.2	0	0

Calculations of amount adsorbed before and after the pressure drop based on the excel solver sheet

Total							
mg/min	600		Time taken to reach required pressure (S):			2140	
					Minutes	35.66667	
Total CO2 feeded (mg) :			21400				
		(mol CO2)	0.48636364				
	P	30					
	V	170		Volume of cylinder	339.4285714		
	R	82.05746					
	Z	0.98					
	T	303			3.142857143		
	Ntheo	0.209307					
	Amount adsorbed		0.27705681				

Where the amount adsorbed is the first value we got during the built up pressure into the bed , where the total amount is the amount during built up in addition to the amount being adsorbed in the pressure drop stage.

V	(cm ³)	170			
		(Atm)			
P _{initial} (bar)	30	29.61	Pr	0.405953992	Note P _{cr} = 7.39 MPA --> 73.9bar T _{cr} = 304.2 K
Temperature (Kelvin)	303		Tr	0.996055227	
Z initial (from graph)	0.87				
R(L·atm·mol ⁻¹ ·K ⁻¹)	82.05746				
PV= ZnRT					
n = PV/ZRT	0.232706				
		(atm)			
P _{final} (bar)	27.5	27.1425	Pr	0.372124493	P _{cr} = 7.39 MPA --> 73.9bar T _{cr} = 304.2 K
Temperature (Kelvin)	303		Tr	0.996055227	
Z Final(from graph)	0.86				
R(L·atm·mol ⁻¹ ·K ⁻¹)	82.05746				
PV= ZnRT					
n = PV/ZRT	0.215794				
N (adsorbed (mol))	0.016912				
Total CO ₂ adsorbed	0.293969				

Amount adsorbed is calculated by determining amount of gas injected into the reactor to reach certain pressure (from the mass flow meter) and subtracting it with the theoretical amount of gas which suppose to be inside the reactor at that pressure and temperature

Where the total amount of gas introduced to the bed is calculated using this formula

$$n_T = \left(\frac{V}{RT} \times \left(\frac{P_{S1}}{Z_1} - \frac{P_{S2}}{Z_2} \right) \right)_{FV}$$

Where Z is the compressibility factor and it can be calculated from

