Preliminary Study on Gas Storage Capacity and Gas-in-Place for CBM Potential in Balingian Coalfield, Sarawak Malaysia

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Abstract

This project focuses on Coal Bed Methane (CBM) potential in Balingian coalfield, Sarawak. One block in Balingian area is picked as an area for preliminary assessment. Liang formation (Balingian Coal) is lignite coal with a mean vitrinite reflectance of 0.32%, coal seam thickness from 0.33- 29.69 ft. According to Geoscience and Mineral Department Malaysia, the moisture content is in between 12.9% to 18.7%, volatile matter varies at 37.8% to 43.4% with fixed carbon ranges from 40.3% to 43.4%. The coal contains a very low ash content of 2.7% and sulphur content less than 1%. Four different core samples were used with porosity and permeability values from 1.58% to 5.12% and 0.15mD to 46.15mD. Gas storage capacity at different pressures was determined from adsorption isotherm test based on modified Boyle's law. Adsorption isotherm test result showed maximum adsorbed methane in coal is 374.62scf/ton at maximum pressure of 1219.58 psia. Linear regression of Langmuir Volume and Langmuir Volume showed 714.29scf/ton and 1024.5psia respectively. Value of maximum absorbed methane used in gas-in-place calculation yields 15.207 Bscf in area of 6.094km^2. The result is compared with other similar coal fields. As a conclusion, Balingian coal field showed a very good prospect to produce first CBM in Malaysia based on this study.

Key Words: Langmuir, Gas storage capacity, CBM and Gas-in-place

1. Introduction

Coalbed Methane (CBM) is categorized as unconventional hydrocarbon which is produced from coal seams. CBM explorations, operations and developments have been started a few decades ago, especially in the United States. Since 1700's, coal mining has started in deeper depth in United Kingdom and a catastrophic methane explosion has occurred. When the coal is mined, estimated 60% to 80% of the combustible gas is emitted into the mine atmosphere where the accumulated gas creates explosion hazards [1]. Ventilation system was the only conventional method practiced during that time when methane is diluted into the air to lower the concentration and vented out to the surface.

In between year 1876 to 1948, it is recorded at least one major US coal mine explosion per year occurs. The deeper, larger and higher rank coalbed are mined, more gas will be emitted, the conventional ventilation possibly may not adequate to control the emission. Thus, more advance technology required to drain the huge amount methane effectively. Prior to this, extensive studies have been carried out until 1970 where the coalbed methane potential is assessed. The first sale of captured CBM to pipeline was started in year 1974 [2]. CBM is a clean-burning fuel which helps to decrease air pollution. The total annual production from 11 coal basins in US has exceeded 1.5 Tcf with more than 15,000 producing CBM wells. This number of production accounted for 10% of annual US natural gas production is reported in 2001 [3]. Similarly, countries like Australia, Canada, United Kingdom, China, India and Indonesia have successfully exploited CBM as source of energy today.

This research presents the preliminary study of CBM potential in Sarawak coal bearing strata through the prediction of gas storage capacity and gas-in-place. The result of gas storage capacity provides a strong level of confidence in coalbed reservoir resource and reservoir evaluation [4]. On top of that, a preliminary stage for gas-in-place analysis will be conducted based on available information such as reservoir drainage area, gross reservoir rock thickness, average in-situ density and average in-situ gas content. The coal structure with its permeability and porosity will be determined experimentally to study the characteristic of Balingian coal.

2. Literature Review

2.1 CBM formation and production

Coal is formed from peat, the deposited plant-derived organic material through coalification. Coalification occurs at different rates in different environments. Biochemical degradation initiates the coalification process but with burial increasing overburden pressures and subsurface temperature cause physiochemical process that continues coalification. As water, carbon dioxide and methane are released, the coal increases in rank, starting from lignite, sub-bituminous, bituminous, anthracite, and graphite. Bituminous coal rank contains the highest gas volume in it.

Coal acts as both the source rock and reservoir rock for methane. Methane is generated by microbial (biogenic) or thermal (thermogenic) processes shortly after burial and throughout the diagenetic cycle which resulting from further burial. Hydraulic pressure, rather than a pressure seal or closed structure (common for conventional oil and gas fields), is the major trapping force for CBM. Coal is extremely porous (openings) but with low permeability (connected openings). Most coals contain methane, but much of it cannot be economically produced without the presence of natural fractures (cleats) to connect the pores. CBM is stored in coal matrices (primary storage) as well as in cleats and natural fractures (secondary storage). Coal cleats are classified geometrically with the primary cleats which are called face cleats that is more continuous and the secondary cleats which are called butt cleats that is less continuous. When the coal bed is depressurised, the gas which is adsorbed in the coal matrices begins to diffuse by Fick's Law [5] and enter the fracture/cleat network. Methane and carbon dioxide are the major components of CBM.

CBM production is usually initiated by pumping out water from the reservoir to allow the gas to desorb from the coal matrix and diffuse to the cleat but some wells may not be economical if too much water has to be pumped. Some coal beds may never be dewatered, depending on the hydrology. If CBM fields are associated with a conventional gas trap, like the Drunkards Wash area in Price, Utah [6], gas flows freely upon completion of the well without the need for dewatering. CBM, unlike conventional oil and gas production, usually shows an increase in the amount of production at first and then steadily declines. As a coal is dewatered, the cleat system progressively opens farther and farther away from the well. As this process continues, gas flow increases from the expanding volume of dewatered coal. Water production decreases with time, which makes gas production from the well more economical.

2.2 Overview of Balingian coalfield

Balingian Coalfield is one of the 4 major coal fields in Sarawak situated at 45km from Sibu town. The first study of the Mukah-Balingian coalfield was begun in 1994 with a very short detail of outcrop study. In 1996 to 2000, Mukah-Balingian coal field was split into two individual reports for further field evaluation. Mukah coalfield is located at northern part of Begrih formation whilst Balingian coalfield is located at the southern part of Begrih formation as shown in the Figure 1[7]

Balingian East Block of Balingian coalfield is located in the north central part of Sarawak which centred at latitude of 2^o 43' and longitude of 112^o 24.5'. The area is located about 30km to 40km to southeast of Mukah town. The evaluation coal resource of Balingian East block was carried out by the Geological Survey of Malaysia from 1996 to 2000. The Liang formation forms the Balingian coalfield is from Upper Miocene age. The Liang formation is composed of conglomerate, sandstone, siltstone, mudstone, shale and lignite which are similar lithological properties to Balingian formation.

The only different between those two formations are poorly consolidated and enriched in conglomeratic bed within the Liang formation. [8, 9] The dip angle of Liang formation showed 12^o to 15^o toward south. There is no major fault/fold except northward propagating fold thrust at the southern of Liang formation due to Belaga formation which is located at the south of Liang Formation

The distribution and orientation of cleats system in a coal field provide important information regarding the pathway of the methane flow in the reservoir. Balingian coalfield has the face cleats strike at NNE-SSW, whilst its butt cleats have a bimodal pattern with cleats trending at NNW-SSE and NE-SW direction. A study has done by Hussein and Dorani [9] showed 11 coal seams were detected with a maximum thickness of 7.39meters. The potential resource is approximately 203.11 million tonnes which consisting 23.35 million tonnes of measured reserve, 82.43 million tonnes of indicated reserve and 97.33 million tonnes of inferred reserve.

2.3 Proximate Analysis and Ultimate Analysis

Proximate analysis is used to determine the percentage of ash, moisture, fixed carbon and volatile matter. The variables are measured in weight percent (wt %) and are calculated in several different basis. This analysis helps to identify the quality of the coal and its rank. As for ultimate analysis, it is to determine the percentage of carbon, hydrogen, nitrogen, sulphur. In addition proximate and ultimate analysis data will be used as the fundamental consideration for future concerns, for instance: coal trading and its utilisations. Both analyses are analysed in accordance to ASTM test method performed in Coal Quality Testing Laboratory by Mineral and Geoscience Department Malaysia, Sarawak. In 1994, the report showed the entire Mukah-Balingian coalfields are sub-bituminous coal but later in 2000, Balingian coal was found to be in lignite. Table 1 shows the summary of comparison between coals from both fields.

The list of ASTM Standard Specification Technique can be found in Appendix A

2.4 Adsorption isotherm test

Adsorption isotherm test is performed to determine the gas storage capacity at different pressure steps and generating a Langmuir equation for Balingian coal. Adsorption isotherm test by using modified Boyle's Law [10] which involve several steps as such as:

- Sample preparation: sample selection, sample crushing (ASTM D1214-89), proximate analysis test, and equilibrium moisture content restoration
- Measuring isotherm adsorption with high purity methane at six pressure steps

Gas storage capacity is evaluated at the equilibrium endpoints for each pressure step. The change in gas storage capacity at the endpoints can be calculated using equation below:

$$\Delta G_s = 32.0368\left[\frac{V_r}{m_c}\left(B_{gr2}^{-1} - B_{gr1}^{-1}\right) - \frac{V_{tv}}{m_c}\left(B_{gtv2}^{-1} - B_{gtv1}^{-1}\right)\right] \ldots \text{(Eq. 1)}$$

Where,

ΔG_s = Change in gas storage capacity, scf/ton

V_r = Reference cell volume, cm³

m_c = Mass of coal, gm

B_{gr2} = Gas formation volume factor at the final reference cell pressure

B_{gr1} = Gas formation volume factor at the initial reference cell pressure

V_{tv} = Adsorption cell void volume, cm³

B_{gtv2} = Gas formation volume factor at the final adsorption cell pressure

B_{gtv1} = Gas formation volume factor at the initial adsorption cell pressure

The gas formation volume factor can be determined using equation below.

$$B_g = \frac{p_{sc} z (T + 459.69)}{p z_{sc} (T_{sc} + 459.69)} \ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 2)}$$

Real gas deviation factor is determined from correlation by Piper L.D.,et al [11] as shown in Appendix B. After all 6 pressure steps with gas content values are recorded, a graph of gas content against end pressure is plotted. In order to determine Langmuir pressure and volume, Equation 3 is used:

$$\frac{P}{V} = \frac{1}{V_L} p + \frac{P_L}{V_L} \ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 3)}$$

Where, $1/V_L$ is the slope and P_L/V_L is the intersection of P/V against end pressure graph
A full procedure and apparatus setup can be referred in Appendix C

2.5 Method for Determining Gas-In-Place

Gas-in-place volume is the total amount of gas stored within a specific reservoir bulk volume. Yee et al. proposed below mathematical equation linking four properties [12] as such:

$G = 1359.7 Ah \bar{\rho}_c \bar{G}_c$ .... (Eq. 4)

Where,

G = gas-in-place, standard cubic feet (scf)
A = drainage area, acres
h = thickness, feet
$\bar{\rho}_c$ = average in-situ density, g/cm³
$\bar{G}_c$ = average in-situ gas content, scf/ton

The first three values can be estimated from boring log, areal map and core analysis. For the fourth value, the gas content can be obtained from the calculated gas content by Equation 4. It is important that the gas in place is corrected for moisture and ash as they adsorb negligible amount of gas. Higher quantities of moisture and ash reduce the amount of gas present in the coal.

3. Problem Statement

Malaysia has been exported about 1 million tonnes of coal from the Sadong Colliery coal field in Sarawak since 1874. Such amount of energy implies a huge resource of coal existed in Sarawak. However, there are no evidence shows that the gas production (to keep the mine safe from explosion) is utilised and highly possible it has been released freely into the air. In 2010, mostly gas field in peninsular Malaysia is depleting. It came into PETRONAS concern to meet the supply demand of natural gas for country usage and exports. Hence, PETRONAS aims to venture in unconventional gas resources and study in year 2010. This study is carried out as preliminary study in order to estimate total resources of CBM available in Balingian Field, Sarawak. In addition, a number of wells were drilled in the Teres and Penipah valleys of the Mukah Coal Field in more that 2000m of Cycle I to Cycle III within Balingian Province had shown an indication of oil and gas existence at a depth of 200m [7].

4. Objectives

The objectives of this research are:

1. To study the permeability and porosity of the coal sample
2. To determine the gas content/gas storage capacity through calculation and experiment
3. To evaluate gas-in-place based on the field data

5. Research Methodology

To achieve these objectives, a research methodology is outlined in Figure 2:

6. Results and Discussions

6.1 Porosity and permeability

Four samples of Balingian coals are examined by using PoroPerm equipment in the lab. Each examined sample is 3 inches in length and 1.5 inches in diameter. The result of the porosity and permeability is shown in Table 2:

A coal that has permeability ranging from 1 mD to 10mD is considered fairly good, whilst above 10md is excellent. In the initial experiment before the 4 above samples examined, a coal core is plugged from the bulk coal by using core plugging equipment with water as coolant. The plugged core has the same length and diameter as of 4 samples. Earlier mentioned in the literature review [13], the plugged core must be kept wet all the times prior to prevent unnatural fracture. However, the limitation of the PoroPerm equipment is the examined core must be a dry core. Hence this core is dried in the oven at 24 ^{o} Celsius for 12 hours. As a result, this core showed a permeability of 1,220.65 mD, a porosity of 14.09% and a pore volume of 7.80 cc.

Such a high permeability and porosity of the core doesn't show the exact reservoir properties because the fractures are not natural fracture due to excessive of coal matrix shrinkage. Palmer and Mansoori explained that the shrinkage of coal matrix is turned out to cause the formation permeability to increase significantly, particularly when the pressure decreases below the desorption pressure [14]. Therefore, 4 above samples above are plugged without coolant in order to maintain the exact core properties. Each core shows different permeability value and porosity value due to the different number of cleats network. Higher permeability and porosity tend to have more cleats network

6.2 Adsorption isotherm result

The gas content is further studied in adsorption isotherm test which 130g of crushed coal is used. The reference volume calculated is 98.77 cc, whilst the calculated void volume in the adsorption cell is 84.22 cc.

Table 3 shows the pressure values in the adsorption cell and reference cell at initial state and final state for every pressure step. Table 4 is the calculated gas formation volume factor for each state of adsorption cell and reference cell. The changes of gas content in each step are plotted in Figure 3. At the end of the pressure step, the total accumulated gas content at 1219.58psia is 374.62scf/ton which is shown in Table 5.

Based on the changes of gas content values in every step, a regression line is drawn on the P/V against P graph as shown in Figure 4 for Langmuir pressure and Langmuir volume value determination. The Langmuir pressure is 1024.5 psia and Langmuir Volume is 714.29 scf/ton. Langmuir volume indicates the maximum level of gas storage capacity and Langmuir pressure is equal to the pressure at which coal storage capacity is equal to one-half the Langmuir pressure.

6.3 Gas-in-place result

1219.58psia is considered as the maximum pressure where 374.62scf/ton of methane can be stored in the coal matrix. By using this gas content value, the value of gas-in-place is calculated as shown in table 6. According to the result above, the values used for the parameters above are based on the limited information such as the average drainage area, average reservoir thickness and average in-situ density

The average drainage area was measured based on the resource evaluation method by US Geological Survey. 400m of radius from each drill hole was drawn on the map to estimate area of influence (measured resources) and the area is measured by planimeter. This is the only option in area determination since there is very limited information [4].

However, in the actual reservoir, there are different types of geologic heterogeneities such as permeability facies change, coal seam pinch out, channel sandstone deposits and fault offset [4]. Thus, such heterogeneities disrupt the lateral coalbed continuity which requires a better and accurate reservoir area analysis. Besides, permeability anisotropy contributes the inaccuracy in drainage area determination. As discussed in literature review, the coal structure contains cleat system which is not uniform throughout the coal in a given reservoir. The spacing, aperture and effective porosity of the cleats strongly affected the reservoir permeability. The permeability and porosity result proven each sample provide different values. As a result, the drainage area may be substantially different from rule-of-thumb well spacing-based area estimation due to permeability anisotropy that causes the effective drainage area around the wellbore to have an elliptical shape. Both geologic heterogeneities and permeability anisotropies are highly site dependent.

Reservoir thickness of each drill hole that encountered coal seams was taken from the lithology test performed by the GeoQuest Sdn. Bhd. An average reservoir thickness was taken in this evaluation.The density of coal is a function of its composition. Similar to the average drainage area, the density properties and coal compositional are not uniform throughout the coalbed reservoir due to geologic variables such as depositional environment, overlying and underlying rock lithologies, coal rank, equilibrium moisture content, mineral matter content and maceral composition. In this evaluation, a rule-of-thumb value of 1.335 g/cm³ is used for the in-situ rock density [15, 16, and 17].

Despite of that, moisture content affects the coal density as well. Moisture in coal reduces its capacity to adsorb. Based on the previous research, bituminous coals have low in-situ moisture content which is less that 10% whereas the sub-bituminous coal has very high in-situ moisture content which is more than 25% [18, 19, 20, 21]. This shows that the moisture content varies inversely proportional to coal rank. For comparison, Powder River Basin sub-bituminous coal has an in-situ moisture content of 27% and an ash content of 5%, hence the density is only about 1.33g/cm³ [20]

6.4 Comparison between Balingian and other similar coalfields

Based on Table 7 in Appendix D, Hawkdun field was compared with Powder River basin field in Manhire, et al’s report due to similar coal characteristic and gas content. Despite low gas content, Powder River basin coals has proven a significant result to successfully developed as a producing CBM fields due to several postive factors. One of them is the very high permeability which is reflected in gas flow rates of between 500 and 5,000 m3/day being reported [22]. The recorded permeability achieved by Powder River basin is between 80 to 200mD. Nevertheless, Government of India has used the similar approach to evaluate their lignite coalfields; Barmer and Mannargudi, for block bidding purpose in developing their CBM projects [23,24,25].

Hence, similar coal rank field, Mannargudi and Hawkdun projected similar gas content measurement by direct method measurements. Mannagudi was reported to have about 977.81Bscf of resources which is quite significant compares to the Fairview Bituminous coalfield in Australia. Nevertheless, the Balingian coal showed a very good CBM resources (GIP) for a very small drainage area of about 6km^2. Hawkdun field has recorded gas storage capacity of 76.8scf/ton at pressure of 3000kPa [26].

Therefore, the ratio of gas storage capacity over pressure of Hawkdun field was used to determine the gas storage capacity of Balingian at similar pressure. As a result, the gas storage capacity of Balingian field is double of gas storage capacity of Hawkdun field. On top of that, Balingian field has an excellent permeability of 46.15mD as it is a one of the contributors to the success of Powder River basin field. Based on these justifications, Balingian field has proven a great potential for futher and detail study.

7. Conclusion and Further Directions

Based on the adsorption isotherm test and gas-in-place calculation, Balingian coalfield yields a very good prospect of CBM potential for further detail study due to several reasons:

a) the highest recorded permeability of 46.17mD
b) the area of 6.0937 km^2 is able to contain a resource of CBM of 95.37 0Bscf

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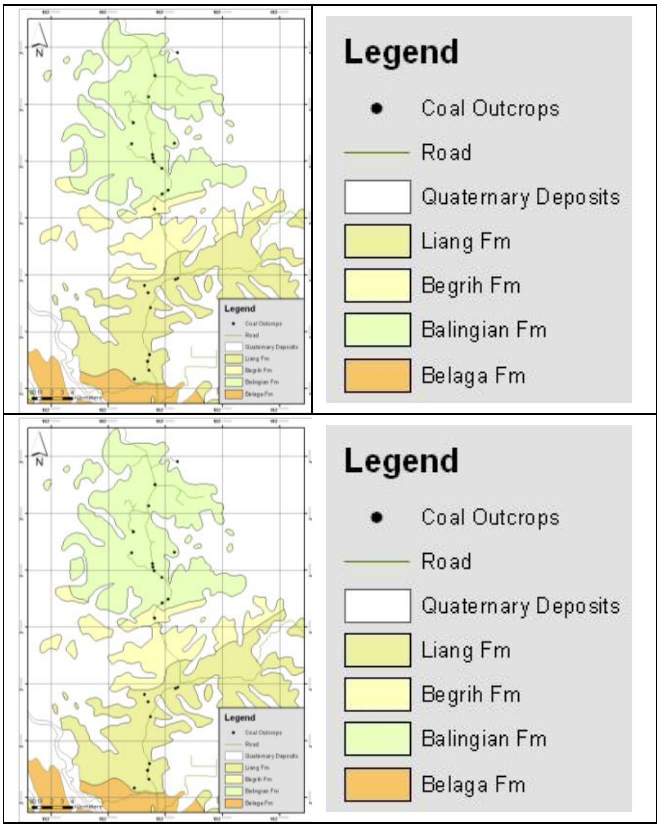


Figure 1- Mukah-Balingian Coalfield map

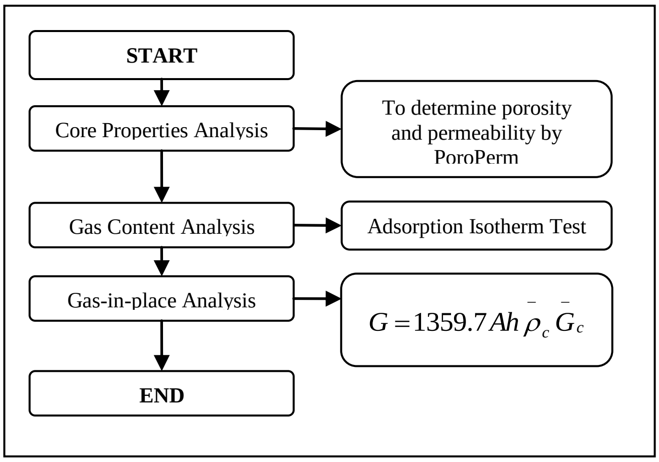


Figure 2- Research methodology

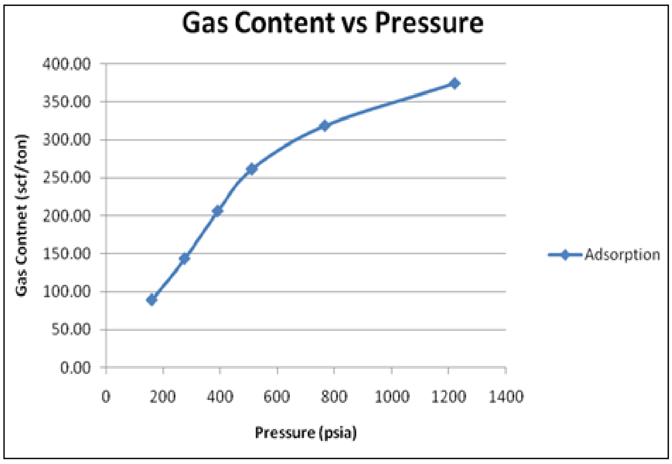


Figure 4- Graph of pressure/gas content against pressure

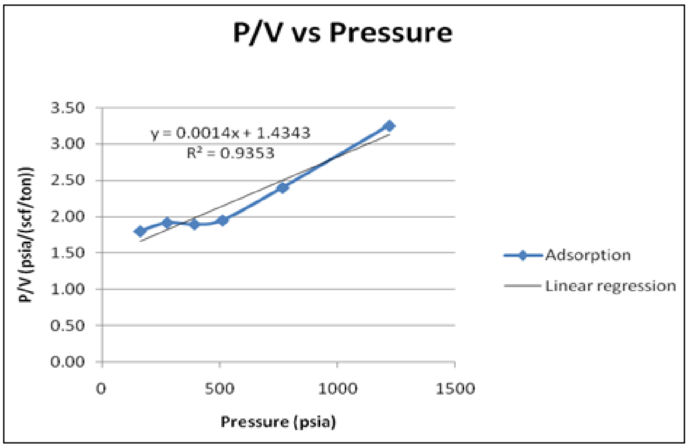


Figure 3- Graph of Gas Content against pressure

Table 1- Comparison of proximate and ultimate analysis

Analysis	**Mukah Coal**	**Balingian Coal**
Total Moisture (dry)	23.3%	23.25%
Total Ash (dry)	22.05%	5.95%
Sulphur content (dry)	1.45%	0.48%
Volatile Matter (dry	36.2%	48.9%
Gross caloric value (dry)	22.22MJ/kg	25.92MJ/kg
Rank	Sub-Bituminous B	Lignite
Vitrinite Reflectance (%Ro)	0.47%	0.32%

Table 2- Porosity and Permeability Result

	Sample			
	A	**B**	**C**	**D**
Porosity %	1.58	3.71	5.12	3.92
Permeability mD	0.15	7.02	46.2	4.32
Pore Volume,cc	1.38	3.17	5.51	2.29

Table 3- Pressure values in adsorption and reference cell for every step

Number of Step	**Reference cell pressure at initial step**	**Reference cell pressure at final step**	**Adsorption cell pressure at initial step**	**Adsorption cell pressure at final step**
	psia	**psia**	**psia**	**psia**
1	285.290	143.570	51.500	159.880
2	343.680	215.420	159.880	274.630
3	488.890	355.970	274.630	390.720
4	629.010	499.840	390.720	510.130
5	990.670	754.800	510.130	765.500
6	1580.670	1187.310	765.500	1219.580

Table 4- Gas formation volume factor in adsorption and reference cell for every step

Number of Step	**Reference cell Bg at initial step**	**Reference cell Bg at final step**	**Adsorption cell Bg at initial step**	**Adsorption cell Bg at final step**
	Bgr1	**Bgr2**	**Bgtv1**	**Bgtv2**
1	0.051	0.105	0.294	0.093
2	0.042	0.069	0.093	0.054
3	0.029	0.041	0.054	0.037
4	0.022	0.029	0.037	0.028
5	0.014	0.018	0.028	0.018
6	0.008	0.011	0.018	0.011

Table 5- Changes of gas content for every pressure step.

Number of Step	**Adsorption cell pressure at final step**	**Gas Content at Step Start**	**Gas Content at Step End**	**Pressure/ Gas Content**
	psia	**scf/ton**	**scf/ton**	**psia/(scf/ton)**
1	159.880	0	88.80	1.80
2	274.630	88.80	143.24	1.92
3	390.720	143.24	206.01	1.90
4	510.130	206.01	261.54	1.95
5	765.500	261.54	318.90	2.4
6	1219.580	318.90	374.62	3.26

Table 6- Gas content and gas-in-place result

Parameters	**Value**
Area, acres	1505.9
Thickness, ft	93.133
Average in-situ density, g/cm³	1.3350
Average in-situ gas content, scf/ton	374.62
Gas-in-place, Bscf	95.370

APPENDICES

Appendix A

MINERAL AND GEOSCIENCE DEPARTMENT MALAYSIA, SARAWAK
COAL QUALITY TESTING LABORATORY

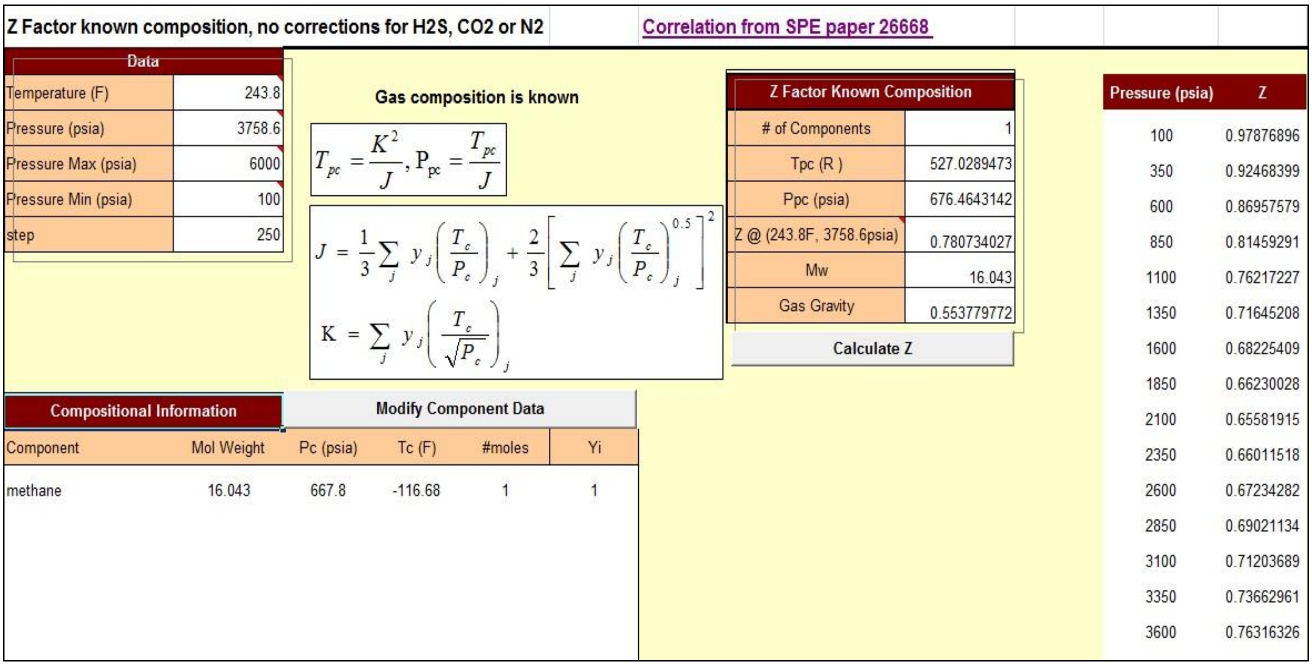
Identification of test method used

Material tested: - Coal and Coke

Type of test	**Standard specification technique/method used**	**Laboratory test method reference**
Total Moisture	**ASTM D 3302 - 07**: Standard Test Method for Total Moisture in Coal	WP/CQL/COAL-01
Moisture	In-house Test Method based on **ASTM D 3173 – 03**: Standard Test Method for Moisture in the Analysis Sample of Coal and Coke	WP/CQL/COAL-02
Ash	In-house Test Method based on **ASTM D 3174 – 04**: Standard Test Method for Ash in the Analysis Sample of Coal and Coke	WP/CQL/COAL-03
Volatile Matter	In-house Test Method based on **ASTM D 3175 – 07**: Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke	WP/CQL/COAL-04
Proximate Analysis (incl. Fixed Carbon)	**ASTM D 3172 – 07**: Standard Practice for Proximate Analysis for Coal and Coke	WP/CQL/COAL-05
Carbon **Hydrogen** **Nitrogen**	**ASTM D 5373 – 02** (Re-approved 2007): Standard Test Methods for Instrumental Determination of Carbon, Hydrogen and Nitrogen in Laboratory Samples of Coal and Coke	WP/CQL/COAL-06
Sulphur	**ASTM D 4239 – 05**: Standard Test Methods for Sulphur in the Analysis Sample of Coal and Coke using High Temperature Tube Furnace Combustion Methods: Method C – High Temperature Combustion Method with Infrared Absorption Procedure	WP/CQL/COAL-07
Gross Calorific Value	**ASTM D 5865 – 07**: Standard Test Method for Gross Calorific Value of Coal and Coke	WP/CQL/COAL-08
Sample Preparation	**ASTM D 2013 – 07**: Standard Practice for Preparing Coal Samples for Analysis	WP/CQL/COAL-12
Ultimate Analysis	**ASTM D 3176 – 89** (Re-approved 2002): Standard Practice for Ultimate Analysis of Coal and Coke	WP/CQL/COAL-13
Calculation of Coal Analysis to Different bases	**ASTM D 3180 – 07**: Standard Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases	WP/CQL/COAL-14

Figure 5- Proximate and Ultimate Analysis Code of Standard

Appendix B



Z Factor known composition, no corrections for H2S, CO2 or N2

Correlation from SPE paper 26668

Data	
Temperature (F)	243.8
Pressure (psia)	3758.6
Pressure Max (psia)	6000
Pressure Min (psia)	100
step	250

Gas composition is known

$$T_{pc} = \frac{K^2}{J}, \mathrm{P}_{pc} = \frac{T_{pc}}{J}$$

$$J = \frac{1}{3}\sum_j y_j \left(\frac{T_c}{P_c}\right)_j + \frac{2}{3}\left[\sum_j y_j \left(\frac{T_c}{P_c}\right)_j^{0.5}\right]^2$$

$$\mathrm{K} = \sum_j y_j \left(\frac{T_c}{\sqrt{P_c}}\right)_j$$

Z Factor Known Composition	
# of Components	1
Tpc (R)	527.0289473
Ppc (psia)	676.4643142
Z @ (243.8F, 3758.6psia)	0.780734027
Mw	16.043
Gas Gravity	0.553779772

Pressure (psia)	Z
100	0.97876896
350	0.92468399
600	0.86957579
850	0.81459291
1100	0.76217227
1350	0.71645208
1600	0.68225409
1850	0.66230028
2100	0.65581915
2350	0.66011518
2600	0.67234282
2850	0.69021134
3100	0.71203689
3350	0.73662961
3600	0.76316326

Compositional Information

Component	Mol Weight	Pc (psia)	Tc (F)	#moles	Yi
methane	16.043	667.8	-116.68	1	1

Figure 6- Screenshot of Z-factor spreadsheet

Appendix C

Experimental Method: Sorption Isotherm/ Langmuir Isotherm Experiment

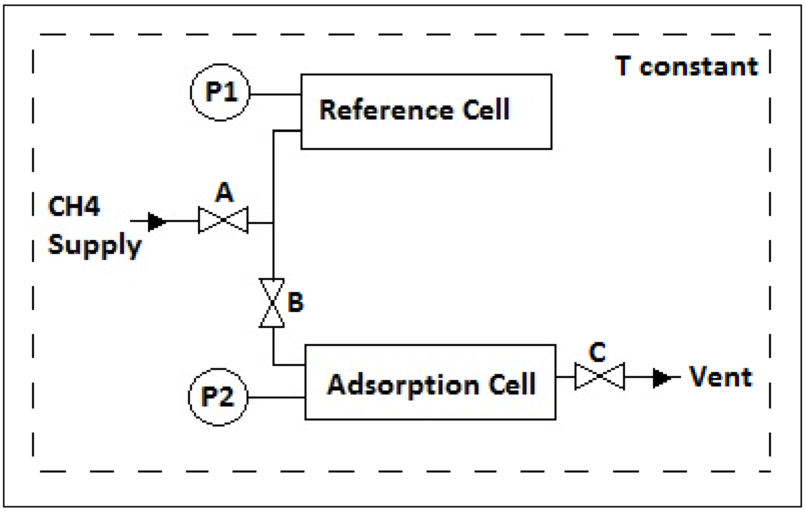


Figure 7- Process flow of adsorption isotherm

The selection and preparation of coal sample before measuring adsorption value is the most critical step. The procedure in sample preparation can be summarized as:

- Sample selection
- Sample crushing
- Proximate analysis
- Equilibrium moisture restoration
- Measuring isotherm

Sample selection

Samples can be taken from drill cuttings or core. In this study, the sample was taken from random location in the field.

Sample crushing

Random samples were crushed together to 60 mesh screen size in order to minimize the time required for methane to diffuse through the sample and to obtain the composite/ uniform sample. The idea of mixing the samples from different coal seams or coal of different ash content is to create desired average.

Proximate Analysis

As reported in literature review, the chemical properties of the coal will be used to quantify the mass of coal present in the isotherm sample. In this case, the proximate value will be taken from the analyses done by the Geoscience and Mineral Department of Malaysia. As a rule of thumb, it is preferable to select samples with an ash content of 15% or lower to avoid non-coal affects upon the diffusion behaviour.

Equilibrium moisture restoration (ASTM 1412: ISO 1018)

1. 150 to 200 gram is air-dried to constant weight
2. The sample then is place in the tray and sprayed with a volume of deionized water approximately equivalent to residual moisture content
3. The residual moisture content is estimated from the difference in the weight of small (approximately 10 to 20 grams), air dried sample before and after drying in a convection oven at 104^o Celsius
4. The sample is then placed in vacuum desiccators over a saturated solution of $K_2SO_4.$ The vacuum desiccator is evacuated to about 30 mm Hg and the temperature is maintained at 30 ± 0.2^o Celcius until the sample reaches a constant weight. If the sample is lignite, it requires 72 hours to reach equilibrium.

Measuring Isotherm

1. Determination of void volume (V_{void}) using helium calibration
   a. The 130g sample is filled into adsorption cell.
   b. The reference cell is injected with helium while the connecting valve B between reference cell and adsorption cell remain closed and allow the pressure to equalize.
   c. The helium is flowed into adsorption cell by opening the connecting valve B until the adsorption and reference cell reaches the thermodynamic equilibrium condition (Valve A is closed)
   d. Total volume of the reference and adsorption cells, V2, initial pressure, P1, equilibrium pressure, P2, and reference cell volume, V1 are determined. V_{oid} = V2-V1 is used to determine the void volume
2. Determination of the adsorption of methane
   a. Both cell is vacuumed
   b. The reference cell is filled with methane while the connecting valve between reference cell and adsorption cell remain closed at 200psi.
   c. The methane is flowed into adsorption cell by opening the connecting valve until the pressure stabilized. Pressure declination is recorded as a function of time in every 30 sec interval.
   d. Once equilibrium is reached, the connecting valve is close. Equilibrium pressure is measured.
   e. Step b to step d are repeated with different pressures with incremental of 100psi each step for 6 step.
   f. Pressure against time graph is plotted.
   g. Gas storage capacity is evaluated at the equilibrium endpoints for each pressure step. Total gas capacity is the sum of the individual end point gas capacities. The change in gas storage capacity at the endpoints can be calculated using the Equation 1.
   h. The gas formation volume factor can be determined using equation below:

$$B_g = \frac{p_{sc} z T}{p z_{sc} T_{sc}} \qquad \text{(Eq. 5)}$$

Where,

B_g = Gas formation volume factor

p_{sc} = Pressure at standard conditions, psia

z = Real gas deviation factor

T = Temperature, ^oR

p = Pressure, psia

z_{sc} = Real gas deviation factor at standard condition

T_{sc} = Temperature at standard condition, ^oR

Appendix D

Table 7- Similar coal rank field in different country

Coalfield (Country)	**Coal thickness (ft)**	**Coal Rank**	**Gas Content (scf/ton)**	**Isotherm (scf/ton)**	**Area (km^2)**	**Resources (Bscf)**
Balingian (Malaysia)	14.85	Lignite	-	133.7	6.094	95.73
Hawkdun (New Zealand)	44.29	Lignite	32.00	76.80	101.3	-
Barmer (India)	213.2	Lignite	128.0	-	2855	9531
Mannargudi (India)	152.2	Lignite	32.00	156.8	766.0	977.8
Powder River (USA)	289.6	Lignite - SubBituminous	38.40	-	66820	150.0