Measurement techniques for carbon dioxide sorption capacity on various coal samples: critical review

M Abunowara1, M A Bustam1, S Sufian1, U Eldemerdash2
1Chemical Engineering Department, Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia
2Chemical Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt

E-mail: 1abunowara1980@gmail.com, 1azmibustam@petronas.com.my
1suriati@petronas.com.my, 2usama.nour@bhit.bu.edu.eg

Abstract. Underground carbon sequestration is proposed as a geologic disposal technique for the long-term storage of CO2 emissions to mitigate climate change and air pollution. Coal bed seams have large CO2 adsorption capacity, long time CO2 trapping and extra enhanced coal-bed methane recovery (CBM). However, CO2 sorption capacity is one of significant steps required to be determined accurately in any feasibility evaluation of carbon sequestration. Hence, in lab scale, there are three methods for CO2 adsorption capacity measurements namely manometric/volumetric, gravimetric and new capsule techniques for gas sorption on variety of sorbents. The manometric and volumetric methods require accurate determination of cell and void volumes and suitable equation of state (EoS). The gravimetric method requires a very accurate sensitive balance and less buoyancy effect and it is the best technique for small amounts (milligrams) of sorbents and the adsorption equilibrium can be mentored. Among all gas adsorption measurement techniques, the newly developed method “capsule method” exhibits the highest CO2 adsorption capacity on Polish coal by 4.08 mmol/g because capsule method that directly measures CO2 uptake of solid coal matrix cylinders, without the application of the equation of state (EoS) for CO2 or volumetric corrections. The main advantage of capsule method is that it is independent of any Equation of State (EoS), and it has no volumetric effects or impurities distort the shape of the gas adsorption isotherm. The disadvantage of capsule method is time-consuming and it is not easy to implement.

1. Introduction
The major excessive emissions of green house gases (GHG5) are emissions of carbon dioxide (CO2) and it is one of the main causes of the global warming and air population. However, the major source of anthropogenic CO2 emissions is the combustion of fossil fuels mainly coal to generate electricity. Therefore, mitigation and controlling CO2 emissions are essential to address the greenhouse gases consequences [1]. Though at present separating and capturing CO2 from the flue gas is costly and requires further research [2]. Hence, it is generally agreed that sequestering CO2 in deep geological formations holds the most viable options for CO2 large-scale storage of the greenhouse gas.

1 To whom any correspondence should be addressed.
Carbon sequestration are including storage of CO\textsubscript{2} in deep sandstone formations, deep saline aquifers, gas-rich shales, active or depleted oil and gas fields with enhanced oil recovery (EOR), deep unminable coal bed seams, methane hydrate formations, salt caverns, other geological formations, or the ocean [2-5]. Furthermore, it is a widely accepted that deep unminable coal bed seams can be used as unconventional gas reservoirs for CO\textsubscript{2} sequestration [6]. It is estimated that the CO\textsubscript{2} storage capacity of unmineable coal bed seams in the worldwide is between 140 and 3000 Gt [6], which could simultaneously displace 1.45 \times 10^{13} \text{ m}^3 of methane reserve [7] and it is reported that one ton of coal can adsorb about 30–35 m\textsuperscript{3} of CO\textsubscript{2} at pressures of 5 to 8 MPa [8].

According to G. X. Wang al et [9] predicted that coal bed seams for CO\textsubscript{2} storage with enhanced coal bed methane (CBM) recovery are usually at the depth of 500–1500 m, with the corresponding reservoir pressure of 5–15 MPa and temperature of 30–100°C. In 2007, N. Siemons et al. [10] reported that the target coal seams for CO\textsubscript{2} injection in Europe is usually at great depth, with correspondingly high reservoir pressure of 6-15 MPa and temperature of 35–50°C. In 2010, J. He et al. [11] reported that the temperatures of potential coal seams typically range from 27-52°C and the depths of the coal seams are greater than 756 m, CO\textsubscript{2} sequestration occurs at supercritical condition (\(T_c = 31^\circ\text{C}, P_c = 73.8 \text{ bar}\)). Hence, higher pressure maintains more gas to remain adsorbed in place meanwhile higher temperature increases the kinetic energy of the system and enables gas molecules to stay in free-state rather than in the adsorbed state [1].

Economically, some of deep coal bed seams may be infeasible for mining due to inadequate coal seam thickness, poor continuity of the area, or adverse geology. However, under the proper conditions, these coal seams can provide adequate sites for CO\textsubscript{2} storage [11]. Hence, the starting step of evaluating the feasibility and capacity of coal bed seams for CO\textsubscript{2} sequestration is to simulate the coal bed seams conditions in laboratory scale. In laboratory scale, one of the significant parameters is the absolute CO\textsubscript{2} storage potential of the coal matrix and it is the sum of the adsorption and pore-filling capacity.

In the lab scale, there are three techniques to measure the CO\textsubscript{2} sorption capacity on coal samples namely manometric/volumetric, gravimetric methods and there is another newly developed method called capsule method. The manometric/volumetric method is most reliable for CO\textsubscript{2} adsorption capacity measurement at above supercritical pressure and temperature condition. The objectives of this work are to present the current methods for gas sorption on different sorbents and to discuss their advantages and disadvantages and to compare the gas sorption on various coal samples and the experimental results of CO\textsubscript{2} adsorption measurements on variety of coal specimens.

2. Methods of gas adsorption measurement

CO\textsubscript{2} adsorption capacity measurement is one of the major steps in assessing the CO\textsubscript{2} potential storage in any geosequestration reservoirs. The volumetric/ manometric and gravimetric are common techniques where have been utilized to measure gas adsorption isotherms of porous materials such as coal that are flooded with CO\textsubscript{2} under unconfined, isostatic conditions. These techniques are usually applied to determine the Gibbs Surface Excess (GSE), i.e. the amount of adsorbed CO\textsubscript{2} present in the coal in excess of the free, bulk phase present at constant pressure and temperature [22].

The manometric/volumetric method requires accurate determination of cell and void volumes. The amount of gas sorbed is recorded by pressure readings (manometric method) or pressure or volume readings (volumetric method). For high temperatures (27 – 427°C) and for corrosive gases and high pressures (50 – 300 bars) the use of metallic sealings (steel, sliver) always recommended and the amount of the sample depends on the sample cell. The manometric method is most widely used for determining gas sorption capacities on coal [12, 13, 16]. The volumetric method is similar to the manometric method [14-16].

In manometric method as shown in Figure 1, the amount of sorbed gas is measured by reading gas pressure. The excess sorption mass \(m_{\text{excess}}\) is the difference between the mass of gas that has been transferred into the measuring cell up to a given pressure step and the “non-sorption” reference mass [16].
Figure 1. Schematic diagram of manometric sorption setup, V denotes valves and P denotes pressure transducers [16].

\[
m_{\text{excess}}^\text{CO}_2 = m_{\text{transferred}}^\text{CO}_2 - V_0^\text{void} \cdot \rho_{\text{gas}}^\text{void}(T,p) \tag{1}\]

The mass transferred from the reference cell into the measuring cell during \(N\) successive pressure steps is given by:

\[
m_{\text{transferred}}^\text{CO}_2 = \sum_{i=1}^{N} V_{\text{ref}} \cdot \left( \rho_i^\text{gas}(p_i,T) - \rho_{i-1}^\text{gas}(p_{i-1},T) \right) \tag{2}\]

The void volume \(V_0^\text{void}\) of the sample cell is determined by expansion of a “non-sorbing” gas, which is typically helium. Helium densities are calculated using the equation of state (EoS) by using the Vander Waals equation with \(a\) and \(b\) parameters. This procedure also provides the skeletal volume \(V_{\text{skeletal}}^\text{sample}\) and the skeletal density \(\rho_{\text{skeletal}}^\text{sample}\) of the sample. For gas sorption isotherms, the void volume multiplied by the density of the gas (or supercritical) phase \(V_0^\text{void} \cdot \rho_{\text{gas}}^\text{void}(T,p)\), yields the “non-sorption” reference mass, i.e. the amount of gas (supercritical fluid) that would be accommodated in the measuring cell if no sorption takes place.

In volumetric method, the amount of sorbed gas is measured by reading gas pressure or gas volume and the schematic diagram of this method is shown in Figure 2. In order to measure gas sorption amount with volumetric method, volume of measuring system has to be measured precisely at first. Then, adsorption amount is calculated from the change of gas pressure inside the measuring system by means of ideal gas equation. Sample handling is easier in volumetric method than in gravimetric method and the thermal equilibrium reaches rapidly in volumetric method. The amount of gas injected \(m_{\text{gas}}^\text{injected}\) can be determined from the pump position as it moves forward. Therefore [16]:

\[
m_{\text{gas}}^\text{adsorbed} = m_{\text{gas}}^\text{injected} - m_{\text{gas}}^\text{unadsorbed} \tag{3}\]

While

\[
m_{\text{gas}}^\text{injected} = \left( \frac{p\Delta V M}{ZRT} \right)_\text{pump} \tag{4}\]

\[
m_{\text{gas}}^\text{unadsorbed} = \left( \frac{pV_0^\text{void} M}{ZRT} \right)_\text{sample cell} \tag{5}\]

Here \(m\) denotes the mass of gas, \(p\) is pressure, \(T\) is temperature, \(M\) is the molar mass of the gas species, \(Z\) is the compressibility coefficient of the pure gas species and \(R\) is the universal gas constant. \(\Delta V\) is the volume change in the pump and \(V_0^\text{void}\) is the volume of the free gas in the sample cell.
In most sorption systems, the excess sorption of the coal sample is the extra amount of gas in the cell than would be present if the coal could not interact with the gas. In volumetric technique, the measurement requires accurate values for the volume of the sample cell, the volume of coal in the sample cell and, in volumetric systems, and the temperature of the system. The volume of the coal is normally calculated from the helium density of the coal; i.e. the density of the coal that is inaccessible to helium [21].

The main advantage of volumetry/manometry is that simple easy to handle. However it needs accurate measurement of the reference and samples. The amount of sorbent material usually needed several grams if only tiny amounts (milligrams) of the sorbent are available then gravimetric measurements strongly recommended. Approach to equilibrium, gas adsorption may last for second, hours or sometime even days and months. The disadvantages of volumetric/manometric adsorption experiments do not give information on the kinetics of the process and small amounts of adsorbent (several milligrams) have shown to be ineffective. They are not practical at extreme low or high pressures as pressure measurements in these regions becomes difficult and accurate of equation of state (EoS) of the sorption gases are not always available [17]. Furthermore, swelling of the coal upon equilibration with CO\textsubscript{2} produces a substantial error in corrections made for the free, bulk phase present in the pores. The reliability of Helium pycnometry as a method to correct for the free, bulk phase (volumetry/manometry) may be questioned, because Helium (He) and CO\textsubscript{2} may not fill the same pore space in coal, and because the probe gas He itself may adsorb to the coal slightly. The thermo-physical properties of pure CO\textsubscript{2} near the critical point, as predicted by the equation of State (EoS), are extremely sensitive to the presence of chemical impurities, in particular to species that are extracted from coal by supercritical CO\textsubscript{2} [22].

In gravimetric method, the amount of sorbed gas is measured by reading sample (sorbent) gravity at constant pressure by means of an accurate balance and less buoyancy effect with the sample either suspended mechanically or by magnetic coupling across the wall of a high-pressure vessel as shown in Figure 3. The maximum amount of amount of adsorbent material is 25g and the temperature ranges 20-250°C and pressures up to 500 bar [18-20].

The excess sorption is determined from the weight change (apparent mass change) of the sample $(\Delta m = m_{\text{measured}}(T,p) - m^0_{\text{sample}})$ recorded during individual sorption steps, where $m^0_{\text{sample}}$ is the original sample mass.

The excess sorption is derived from its apparent weight change by a buoyancy correction based on the skeletal volume $(V^0_{\text{sample}})$ of the sample, corresponding to the same reference state as in the manometric procedure. The determination of the skeletal density or volume is performed with helium. The excess sorbed mass is then given by:

$$m_{\text{excess}}^{\text{gas}} = \Delta m + V^0_{\text{sample}} \rho_{\text{gas}}(T,p), \text{ or}$$

where $\rho_{\text{gas}}(T,p)$ is the gas density at temperature $T$ and pressure $p$. 

\[\text{(6)}\]
The advantage of gravimetry when compared to volumetry/manometry system is that with gravimetry it is possible to observe the approach to equilibrium during the adsorption process at the balance’s data display. Therefore, one can choose arbitrarily a certain small fraction of the pure sorbent sample’s mass and a certain time interval and define technical adsorption equilibrium of the system. The main disadvantages of gravimetric are the buoyancy effects, the construction of gravimetric system are costly and high sensitivity to external surrounding environment. Despite attempts made to enhance the accuracy of GSE methods in coal-CO$_2$ systems, these issues are extremely difficult to resolve. Thus, there is an obvious demand for an independent method to determine CO$_2$ uptake by coal [22].

Therefore, in 2011, Hol et al. [22] fabricated a new, direct method of measuring the uptake of CO$_2$ by coal (i.e. by sorption plus pore-filling). The description of the capsule method, the ductile metal capsule is placed in the compaction cell using a capsule holder as shown in Figure 4. A cylindrical coal sample, 4 mm in diameter and 4 mm in length, is jacketed in a tightly fitting, annealed gold capsule and exposed to CO$_2$ at constant pressure and temperature. Sorption induced swelling of the sample is accommodated by ductile deformation of the capsule. Once the coal is saturated, the capsule is sealed by mechanical loading and the external CO$_2$ pressure removed. This allows the CO$_2$ to desorb from the coal and flow into an Al-foil bag attached to the capsule. The volume of the bag, and hence the amount of CO$_2$ stored in the coal sample, is determined using the Archimedes method.

While the capsule method is time-consuming and not easily executed, the advantage is that it is independent of any Equation of State (EoS), and that no volumetric effects or impurities distort the shape of the isotherm.

Figure 3. Schematic diagram of magnetic suspension balance (MSB). EM = electro magnet; PM = permanent magnet; TS = titanium sinker [18].
To calculate the total CO\textsubscript{2} uptake of the samples, they first determined the trapped CO\textsubscript{2} volume by subtracting the empty capsule/bag volume from that measured in the inflated state. The volume of CO\textsubscript{2} trapped in the bag at ambient conditions (V\textsubscript{bag}, ml) was then multiplied by the density of pure CO\textsubscript{2} (ρ\textsubscript{CO\textsubscript{2}} in mmol ml\textsuperscript{-1}) at the ambient conditions (P,T\textsubscript{ambient}) pertaining during weighing, and the result divided by the mass of the sample m\textsubscript{0} in grams, to obtain [23]:

\begin{equation}
N = \frac{V_{bag} \cdot \rho_{CO_2} (P,T_{ambient})}{m_0}
\end{equation}

Where N is the total CO\textsubscript{2} uptake in mmol g\textsuperscript{-1} or mol kg\textsuperscript{-1}.

This newly developed technique called capsule method that directly measures CO\textsubscript{2} uptake of solid coal matrix cylinders, without the application of the equation of state (EoS) for CO\textsubscript{2} or volumetric corrections of any kind and it can determine the uptake of any adsorbate by any (swelling) adsorbent, including shale and clay cap rocks.

3. CO\textsubscript{2} adsorption capacity on various coal samples

In lab scale, the manometric, volumetric and gravimetric are common methods and still have being utilized by many researchers for determining gas sorption on different sorbents. In 2010, J. He et al. [24] carried out experiments to measure CO\textsubscript{2} adsorption/desorption isotherms on anthracite coal samples (Kyungdong, Korea) using a static volumetric method at 25°C (298 K) and 45°C (318 K), and up to 15 bar (150 atm).

The adsorption of CO\textsubscript{2} is favorable at low temperatures and dry coal conditions. CO\textsubscript{2} adsorption capacities on wet and dry coals are 1.39 and 1.49 mmol/g respectively as shown in Figure 5. In wet coal, the dissolution of H\textsubscript{2}O in the CO\textsubscript{2} phase, absorption of CO\textsubscript{2} in the aqueous phase, and coal structure changes affected the estimation of adsorption amount, especially under supercritical condition.
In 2013, H. H. Lee et al. [25] utilized a volumetric gas chromatographic method to measure the excess sorption amount of anthracite Kyungdong coal samples from South Korea and samples size range was 150–500 μm under 45 °C (318K) and 65 °C (338K) and up to 13 MPa. They found out that the total excess adsorbed amount and isotherm shape of mixture on dry and wet coal was similar to the results of pure CO$_2$. Beyond 4 MPa (40 bar), all curves showed a similar shape due to the increased holdup ratio of the gas phase to the sorbed amount. Therefore the total excess adsorbed amount and isotherm shape of mixture on dry and wet coal were similar to the results of pure CO$_2$ as shown in Figure 6 and Figure 7. The moisture of the coal reduced the sorption amount compared to dry coal in the mixture system, showing a similar moisture effect on the isotherm of pure CO$_2$ in the same range of fluid density.

**Figure 5.** Comparison of adsorption and desorption of CO$_2$ between dry coal and wet coal (3.64%) at 45°C (318 K) with respect to pressure [24]. G: subcritical and SC: supercritical.

**Figure 6.** The highest excess adsorbed amount of CO$_2$ and CH$_4$ pure and mixture, on dry coal at 45°C (318 K) as a function of density [25].
Figure 7. The highest excess adsorbed amount of pure CO\textsubscript{2} and CH\textsubscript{4}, and their mixture on wet coal at 45°C (318 K) as a function of density [25].

In 2013, V.N. Romanov et al. [26] utilized manometric technique to measure CO\textsubscript{2} adsorption capacity of coal samples from Central Appalachian Basin, US. The CO\textsubscript{2} adsorption measurements were carried out at 55 °C by introducing CO\textsubscript{2} into the cell to build the pressure step-wise up to 12 MPa. The maximum CO\textsubscript{2} adsorption capacity is 0.97 mmol/g-dry-ash free (daf) as shown in Figure 8. The role of CO\textsubscript{2} dissolution in pore water appears to be marginal.

Figure 8. CO\textsubscript{2} excess sorption isotherms (dry basis) on wet and dry Appalachian coals [26].

In 2013, S. Hol et al. [22, 23] newly developed technique called capsule method that directly measures CO\textsubscript{2} uptake of solid coal matrix cylinders. The experiments were performed on high volatile bituminous coal, exposed in the Brzeszcze mine, in the Upper Silesian Basin of Poland. The samples
were saturated with CO$_2$ at a fixed CO$_2$ pressure between 0 and 16 MPa and a temperature of 40 °C. The total uptake of CO$_2$ measured using the capsule method continuously increases as a function of increasing CO$_2$ pressure, up to a value of 4.08 mmol/g coal at 18.10 MPa CO$_2$ of pressure meanwhile 4.08 mmol/g by using manometric technique meanwhile 3 mmol/g by using manometric technique as shown in Figure 9.

**Figure 9.** CO$_2$ comparison between single capsule method and manometric method [23].

In 2012, Weniger et al. [27] conducted the CO$_2$ adsorption isotherms using manometric technique to measure high-pressure CO$_2$ adsorption isotherms at 45 °C and at 6 to 10 MPa on as-received coal samples from the Paskov and ČSM mines from Upper Silesian Basin (Czech Republic). The excess sorption capacities of moisture-equilibrated coals ranged from 0.8 to 1.16 mmol/g-daf and the maximum excess sorption ($n_{\text{max}}$) values measured on as-received coals range from 0.96 to 1.41 mmol/g for CO$_2$. A comparison of CO$_2$ adsorption isotherms measured on as-received and moisture-equilibrated coal is given in Figure 10. This reduction of CO$_2$ sorption capacity is due to the steep increase in the specific density of supercritical CO$_2$ in this pressure range [27-29].

**Figure 10.** CO$_2$ sorption isotherms for as-received (open symbols) and moisture equilibrated
(solid symbols) coal from Paskov mine (squares) and ČSM mine (circles) [27].

In 2009, Kelemen and Kwiatek [30] measured CO\textsubscript{2} adsorption on coal samples at 30 °C, dry coal at 75°C and 1.8 MPa using gravimetric gas sorption measurements (Hiden IGA gas sorption system). The rate of gas adsorption for coal varies with the size of coal particles that are smaller than the fissure network of the coal. Gas adsorption isotherm experiments are usually conducted using powdered coal samples to assure that equilibrium is rapidly approached. As shown in Figure 11, the maximum adsorption capacity of CO\textsubscript{2} is 1.40 mmol/g [30, 31].

![Figure 11.](image)

**Figure 11.** Comparison between CO\textsubscript{2} adsorption results using 75–150 µm powder and ~7 mm block dry Pocahontas Argonne Premium coal [30].

In Table 1 a summary of the maximum of CO\textsubscript{2} adsorption capacities on various coal samples and it is obvious that wet coal samples always have less CO\textsubscript{2} adsorption capacity compared to dried coal samples because the energetic active sorption sites occupied by water [15, 32]. The comparison of all dry and wet coal samples are depicted in Figure 12 and Figure 13. However it noticed that the dry Polish coal sample has the highest CO\textsubscript{2} adsorption on coal by 4.08 mmol/g compared to the other coal samples.

| Coal sample                | Technique     | Maximum CO\textsubscript{2} adsorption (mmol/g) | Ref. |
|----------------------------|---------------|-----------------------------------------------|------|
| Dry Polish coal            | Capsule       | 4.08                                          | [23] |
| Dry Korean coal            | Volumetric    | 1.49                                          | [24] |
| Wet Korean coal            | Volumetric    | 1.39                                          |      |
| Dry Korean coal            | Volumetric    | 1.48                                          | [25] |
| Wet Korean coal            | Volumetric    | 1.38                                          |      |
| Dry Appalachian coal       | Manometric    | 0.97                                          | [26] |
| Dry Czech Republic coal    | Manometric    | 1.41                                          | [29] |
| Wet Czech Republic coal    | Manometric    | 1.16                                          |      |
| Dry Pocahontas coal        | Gravimetric   | 1.40                                          | [30] |
4. Conclusions
The volumetric/manometric is common method for CO\textsubscript{2} adsorption isotherms at high pressures and temperatures on various sorbents because they easy to handle and reach thermal equilibrium rapidly. However, it requires an accurate determination of cell and void volumes and elimination of Equation of State (EoS) errors and small amounts of sorbent are ineffective. Thus, when the amounts of sorbent are small (milligrams) the gravimetric technique is strongly recommended and the approach to equilibrium during the adsorption process can be mentored. The other new capsule method is independent of any equation of State (EOS), and no volumetric effects or impurities distort the shape of the isotherm but it is time-consuming and not easily executed. Therefore, it is noticed that dried Polish coal sample using new capsule method has the highest CO\textsubscript{2} adsorption by 4.08 mmol/g. The
presence of moisture in coal reduces the CO$_2$ adsorption on coal significantly and it makes coal to swell. Hence, wet coals adsorb less CO$_2$ compared with the dried coals because the water molecules occupy coal’s pores. The oxygen-containing functional groups are preferentially occupied by water in moist coal due to its polarity. In coal samples, the low and medium coal ranks usually have high affinity for adsorbing CO$_2$ than high coal rank (anthracite) due to the low and medium coals have higher surface area and higher oxygen functional groups. All CO$_2$ adsorption on different coal samples show that there are decline in CO$_2$ adsorption on coal after exceeding the CO$_2$ its supercritical condition. This is due to the enormous increase the specific density of CO$_2$. Furthermore, coal from different coal mine has different physical properties “anisotropic” hence more investigations about the interactions of subcritical and supercritical CO$_2$ with wet and dry coals should be conducted. In future work, CO$_2$ adsorption isotherms on coal using new techniques such as capsule method should be explored. Moreover, the effect of impurities such as H$_2$S, SO$_2$ and hydrocarbons on CO$_2$ sorption onto different coal should also be investigated.

5. References
[1] Vishal V, Singh T N and Ranjith P G 2015 Fuel 139 51–58
[2] Harbin S, Twomblly N J, West R D and Malhotra V M 2015 Fuel 150 131–138
[3] Liu C J, Wang G X, Sang S X, Gilani W and Rudolph V 2015 Fuel 139 125–132
[4] Day S, Duffy G, Sakurovs R and Weir S 2008 Int. J. Greenh. Gas Control 2 342–352
[5] Li X, Fang Z, 2014 Int. J. of Coal Sci Technol. 1 93–102
[6] Brown T D, Harrison D K., Jones J R and LaSota K A 2007 Int. J. Environ. Pol. 29 474–483
[7] White C M, Smith D H, Jones K L, Goodman A L, Jikich, S A, LaCount R B, DuBose S B, Ozdemir E Morsi, B I and Schroeder K. T 2005 Energ. Fuels 19 659–724
[8] Cook P J, Rigg A and Bradshaw J 2000 Aust. Petrol. Prod. Explor. Associate J. 40 654–666
[9] Wang G X, Wei X R, Wang K., Massarotto P and Rudolph, V 2010 Int. J. Coal Geology 83 46–54
[10] Siemons N, Wolf, Karl-Heinz A A, Bruining J 2007 Int. J. Coal Geology 72 315–324
[11] He J, Shi Y, Ahn S, Kang J W and Lee C-H 2010 J. Phys. Chem. B 114 4854–4861
[12] Harpalani S, Prusty B K, and Dutta P, 2006 Energy and Fuels 20 1591–1599
[13] Li D, Liu Q, Weniger P, Gensterblum Y, Busch A, and Krooss B M 2010 Fuel 89 569–580
[14] Ozdemir E and Schroeder K 2009 Energy & Fuels 23 2821–2831
[15] Reeves S, Gonzalez R, Gasem K A M, Fitzgerald J E, Pan Z, Sudibandriyo M and Robinson Jr, R L 2005 ICBM Symposium Tuscaloosa Tuscaloosa Alabama
[16] Busch A and Gensterblum Y 2011 Int. J. Coal Geology 87 49–71
[17] Sudibandriyo M, Pan Z, Fitzgerald J E, Robinson Jr, R L and Gasem K A M 2003 Langmuir 19 5323–5331
[18] Charrière D and Behra P 2010 J. Colloid Interf. Sci. 344 460–467
[19] Ottiger S, Pini R, Storti G, Mazzotti M, Bencini R, Quattrocchi F, Sardu G and Deriu G, 2006 Environ. Prog. 25 355–364
[20] Pini R, Ottiger S, Burlini L, Storti G and Mazzotti M 2010 Int. J. Greenh. Gas Control 4 90–101
[21] Sakurovs R, Day S, Weir S, 2009 Int. J. Coal Geology 77 16–22
[22] Hol S, Peach C J, Spiers C J, 2011 Energy Pro. 4 3125–3130
[23] Hol S, Gensterblum Y and Spiers C J 2013 Fuel 105 192–205
[24] He J, Shi Y, Ahn S, Kang J W and Lee C-H 2010 J. Phys. Chem. B 114 4854-4861
[25] Lee H-H, Kim H-J, Shi Y, Keffer D and Lee C-H 2013 Che. Eng. J. 230 93–101
[26] Romanov, V N, Hur T-B, Fazio J J, Howard B H and Irdi G A 2013 Int. J. of Coal Geology 118 89–94
[27] Weniger P, Francu J, Hemza P and Krooss B M 2012 Int. J. Coal Geology 93 23–39
[28] Bae J S, Bhatia S K., 2006 Energ. Fuel. 20 2599–2607
Acknowledgments
The authors gratefully acknowledge the financial support provided for this research study through E-science grant (0153AB-B41), Centre of Postgraduate Studies (CGS), Universiti Teknologi PETRONAS (UTP) and Ministry of Science, Technology and Innovation (MOSTI), Malaysia.

[29] Gensterblum Y, van Hemert P, Billemont P, Charrière D, Li D, Busch A., Krooss B M, De Weireld G and Wolf K.-H A A 2009 Carbon 47 2958–2969
[30] Kelemen S R and Kwiatek L M  2009 Int. J. of Coal Geology 77 2–9
[31] Goodman A L, Busch A, Duffy G J, Fitzgerald J E, Gassem K A M, Gensterblum Y, Krooss B M, Levy J, Ozdemir E, Pan Z, Robinson Jr R L, Schroeder K., Sudibandriyo M and White C M 2004 Energ. Fuel. 18 1175–1182
[32] Liu Y, Wilcox J, 2012 Environ. Sci. Tech. 46 1940–1947