Partial coal pyrolysis and its implication to enhance coalbed methane recovery, Part I: An experimental investigation

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Highlights

- Feasibility of partial coal pyrolysis for ECBM was evaluated.
- Improvement of petrophysics for coal reservoir was discussed.
- A suitable temperature for ECBM was selected.

Abstract

This paper examines the feasibility of combining a process known as enhanced methane recovery with partial coal pyrolysis to improve the petrophysics of coal seams and ultimately extract higher methane yields with accompanying pyrolysis gases. Partial pyrolysis for coal gas generation changes the pore and fracture structure, which in turn affect the permeability. A series of laboratory experiments on three coal rank samples monitored the changes in pore structure and permeability accompanying coal pyrolysis. Thermogravimetry–mass spectrometry (TG–MS) analysis evaluated mass loss and product composition. The pore and fracture structure evolution was determined by a combination of mercury intrusion porosimetry (MIP), scanning electron microscope (SEM) and methane adsorption capacity measurements on heat-treated coal blocks of ~100 g. The pore volume and methane adsorption capacity of LRC specimen (0.56% Ro) with 10 °C/min and a hold time of 30 min experienced slight changes during the heating process from 25 °C to 400 °C, but when heated from 400 °C to 800 °C, the pore volume in the LRC specimen greatly increased and the mercury-determined total porosity went from 36% at 400 °C to 43% at 800 °C. The permeability of the specimens at the temperature range of 300–400 °C increased exponentially with temperature due to the generated pore–fracture system. The sample LRC (800 °C) with the highest mercury-determined pore volume possessed the lowest methane capacity (19.45 cm³/g) due to the maximum adsorption volume of pyrolyzed coal obtained from the Langmuir model was related not only to the pore structure but also to the extent of graphitization. Therefore, they may have significant implications for enhanced coalbed methane (CBM) recovery.

1. Introduction

Coalbed methane recovery before coal extraction is very important from greenhouse gas emission, assistance in development of gas industry, safety and economic of mining point of view [1–3]. Enhanced coalbed methane (ECBM) recovery from coal seams may consist of a multi-branch horizontal well, with applications of CO2 sequestration, hydrofracturing, biotechnology and heating (steam injection and coal burning) etc. to store gases or enhance permeability/methane production. These methods have associated environmental and economic challenges. Coal pyrolysis is an alternative approach and is a component of underground coal gasification (UCG) [4–6]. This method of gas production produces CH4, H2 and CO2 from the thermochemical decomposition and gasification of organics at high temperatures in the absence of oxygen, which is similar as kerogen pyrolysis in petroleum field [7–10]. A similar approach where only the pyrolysis stage is performed could be a promising option for enhancing CBM recovery. Different physical and thermochemical transformations occur at elevated temperatures: (1) the first stage (25–300 °C), is the dry gas phase. Here, moisture and a small amount of adsorbed gases (including CH4...
and N₂, etc.) desorb from the matrix pores and cleat the system until ~200 °C. Thus, the coal structure does not change significantly. From 200 °C to 300 °C, thermal decomposition occurs for the low-rank coals such as lignite; (2) the second stage (300–550 °C), the coal pyrolysis phase has decomposition reactions, forming gases and tars. Before 400 °C, coal may soften, and viscous plastic mass can form. In the range from 400 to 550 °C, coal gas evolves and coal tar precipitates from the thermally decomposed products. The residual substance in coal gradually stiffens and solidifies as char. Gas produced in 450–550 °C range contains light aromatic hydrocarbon and long chain fatty mass. The petrophysics of coals (including pore structure, fractures and permeability etc.) changes during this phase [6,11–13]. The condensation reaction during the process of the formation of char is not very obvious; (3) in the third stage (550–1000 °C), polycondensation reactions occur (also called secondary generation phase), as well as the carboccoal transition phase. During this phase, carboccoal aromatic sizes increase, the arrangement of aromatic layers often become more ordered, true density increases and a high degree of aromatization occurs along with an of increasing metallic luster. The gas generation here is associated with the thermal decomposition of coal molecule functional groups. Complex organics are pyrolyzed into liquids and gases, which flow/burst out of the particles. Additionally, this stress and mass loss creates more pores and fractures. Thus, the permeability of the pyrolyzed coal is changed.

To accurately and continuously acquire the suitable maximum temperature for enhancing CBM recovery, thermogravimetry coupled with a mass spectrometry (TG–MS) was adopted to analyze the organic decomposition products from different rank coals at elevated temperatures (25–1200 °C) to obtain structural information. Secondly, methane adsorption profiles were determined by a programmed gas adsorption analysis rig. At the same time, the pore structures including pore volume, pore size distribution, porosity and permeability of coals during pyrolysis are investigated with increased temperatures from 25 °C to 800 °C. The feasibility of partial coal pyrolysis for low rank coal (LRC) will be focused due to its low gas content and shallow burial depth.

2. Experimental methods

2.1. Coal sampling

Three coal samples with a volume of approximately 40 × 40 × 40 cm³ were directly collected from three different rank coals including one low-rank coal (LRC, 0.56% R₉,m) and one medium rank coal (MRC, 1.68% R₉,m) and one high rank coal (HRC, 2.59% R₉,m). LRC originated from the southern Junggar basin, NW China; MRC is collected from Ordos basin, North China; and HRC comes from Qinshui basin, North China. All samples were carefully packed and taken to the laboratory for experiments. Each sample was carefully preserved in an intact form.

2.2. TG–MS during coal pyrolysis

Thermogravimetry–mass spectrometry (TG–MS) analysis was conducted by a Rigaku TG–DTA coupled with an Omnistar MS. TG was linked to the programmed furnace, which can collect the continuous weights of samples and execute the data analysis. The TG has a temperature range of 25–1200 °C. The MS has a Nier type enclosed ion source, two detectors and a triple mass filter, which was controlled by computer. The two rigs were coupled by a transfer line leading from the TG to the MS. Generated gases in the TG rig can flow into the MS rig through the transfer line in a few seconds later. The MS need just very small fractions of the gases [14]. The TG conditions used to study the relationship between the structure and gas compositions were heating rate of 10 °C/min at the temperatures of 25–1200 °C; sweep nitrogen, 60 cm³/min; retention time, 30 mins; constant sample volume weighing 25–50 mg. The MS was scanned over a range of 0–100 amu with measurement intervals of approximately 19 s. The characteristics of the products of coal pyrolysis were determined vs. the elevated temperature in the multiple ion detection modes.

2.3. Microscopy and MIP analysis

Vitrinite reflectance (R₉,m) and fracture analyses were conducted as previous research [15]. Coal compositions, proximate and ultimate analyses of used coals are documented in Table 1.

Three coal samples with a volume of approximately 40 × 40 × 40 cm³ were directly collected from three different rank coals including one low-rank coal (LRC, 0.56% R₉,m), one medium rank coal (MRC, 1.68% R₉,m) and one high rank coal (HRC, 2.59% R₉,m). LRC originated from the southern Junggar basin, NW China; MRC is collected from Ordos basin, North China; and HRC comes from Qinshui basin, North China. All samples were carefully packed and taken to the laboratory for experiments. Each sample was carefully preserved in an intact form.

2.4. Methane adsorption measurement

Methane adsorption on coal samples was conducted at 25 °C with the pressure range from 0 MPa to 10 MPa. Before the adsorption experiment, the crushed sample (60–80 mesh) was dried overnight at 50 °C and then degassed at 25 °C for 1 h under a vacuum. Approximately 100 g were used for each measurement. Methane adsorption isotherms were measured using the Isotherm Measurement System (KTI100–40HT). The experimental procedure and the helium calibration for pore volume in coals were described in the previous research [15,21]. Adsorbed methane at a given pressure was similar to the measurement of the pore volume, which was finished when the pressure approached 10 MPa. Each process was repeated two or three times for data accuracy [22,23] and was analyzed using the Langmuir model to obtain adsorption parameters for each sample [24].

![Table 1](image)

<table>
<thead>
<tr>
<th>Samples No.</th>
<th>R₉,m (%)</th>
<th>Proximate analysis wt.% (ad)</th>
<th>Ultimate analysis wt.% (daf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>V</td>
<td>A</td>
</tr>
<tr>
<td>LRC</td>
<td>0.56</td>
<td>0.74</td>
<td>9.58</td>
</tr>
<tr>
<td>MRC</td>
<td>1.68</td>
<td>1.19</td>
<td>11.64</td>
</tr>
<tr>
<td>HRC</td>
<td>2.59</td>
<td>2.24</td>
<td>5.34</td>
</tr>
</tbody>
</table>

Note: M-Moistures; V-Volatiles; A-Ash; FC-Fixed Carbon; C-Carbon; H-Hydrogen; N-Nitrogen; St-Total sulfur; ad-air dry basis; daf-dry ash for free basis.
3. Results and discussion

3.1. Microscopy and SEM

The vitrinite reflectance values ($R_o$, %) for the coal samples are shown in Table 1. They range from thermally immature 0.56–2.59% in the southern Jungar basin, southeastern Ordos basin and southern Qinshui basin. Fig. 1 shows SEM micrographs of coal samples at elevated temperatures. There was a slight difference in the pore morphology at the different temperatures (25°C, 200°C, 400°C, 600°C and 800°C). Compared to LRC (25°C), LRC (200°C) and LRC (400°C), the surface morphology of LRC (600°C) and LRC (800°C) looked spongy, indicating that the porosity of pyrolyzed coal was developed and the development of pores depended on the heating temperatures, which was consistent with the result of mercury intrusion porosimetry. The heat treatment during pyrolysis leads to changes in pore structure, such as the pores enlargement and pore creation. The closure or partial closure of pores due to the thermal expansion at low temperature (<200°C) may also occur [13]. As shown in Fig. 1, the pore morphology determined by SEM reaches the plateau of its maximum size at 600°C, which means that 600°C is enough to improve the coal reservoir for LRC sample. Thus it would provide additional gas adsorption or storage sites and affect the gas transport in an important way.

![Fig. 1. Pore morphology of LRC sample at different temperatures from SEM.](image)

3.2. Gas generation and gas types

During the heating process, many changes occurred including coal structure, coal organic composition, volatiles and moistures adsorbed in the coal, which may physically alter the movement of methane in coals during the adsorption process [25,26]. Thus Fig. 2 depicts the weight change of the original coal due to the change of thermal reaction during the process of coal pyrolysis at a temperatures range of 25–1200°C under the flow of nitrogen. The heating not only removed volatiles and moistures but also resulted in alterations of the pore structure during the low heating process (lower than 200°C), suggesting that the removal of volatiles and moistures produced more micropores. From TG–MS curve, the weight change was negligible during this low heating stage.

Previous research [6,13] found that dehydration mainly occurs below 350°C, together with a small amount of other gases. Extensive evolution of gases had taken place in the range of 400–800°C, which caused the stacking in coal structure [27]. The major gases generated during coal pyrolysis contain $H_2O$, $CH_4$, $CO_2$, $C_nH_{2n}$, $H_2$ (Fig. 2). Oxocarbon decreased gradually with increasing temperature, reaching up to 70% when the temperature hit 350°C, and then going down to 10–30% when the temperature arrived at 500°C. In the pyrolysis process, $C_2$ ($C_nH_{2n}$, $n = 2$) was reduced when the temperature reached 450°C. The methane emissions increased with
increasing temperature from 300 °C, reaching a peak at ~400 °C and accounting for 50–60% of the mass. The generation of CH\textsubscript{4} originated from the thermal reaction when the temperature is normally lower than 700 °C:

\[
\text{Coal} - \text{CH}_3 + \text{H}^- \rightarrow \text{CH}_4
\]  

C(solid) + 2H\textsubscript{2} \rightarrow \text{CH}_4

Methane was mainly generated at this stage, as shown in Figs. 2 and 3. Thus a suitable treatment temperature for enhanced coalbed methane recovery should be <700 °C, which was also accompanied by the changes in accessibility of the pore volume. Although it could be expected that heating could improve the pore accessibility to some extent and generate much gases, the accompanying tar production may condense and could block the flow paths of the pores [27–29], thus the well completion should start after the temperature of coal reservoir has cooled down.

3.3. Petrophysics of coal reservoir during pyrolysis

Coal as a porous medium with economic interest has been widely researched for many years, especially for its petrophysics including pores, fractures, diffusivity and permeability [11,15,26,30]. However, the petrophysical changes associated with

![Fig. 2. Weight change and gas composition during pyrolysis for LRC sample.](image1)

![Fig. 3. The variable gases composition from the pyrolysis of LRC sample.](image2)

![Fig. 4. Pore size distribution of MIP for different rank coals at different temperatures.](image3)
coal pyrolysis are much different from those occurring in normal stress situations during mining or CBM exploitation [12,31,32]. Complex physical and chemical changes happen during the process of coal pyrolysis, and these greatly alter the fracture and pore structures of the coal along with the mass generation including gases or heavy hydrocarbons [12,33].

3.3.1. Pore structure and fractures

Pore size distribution with elevated temperatures is shown in Fig. 4, which was acquired by MIP. To provide a better understanding of the effects of pore structure on both gas adsorption and permeability, a combined classification for coal pore size is used in this work: super micropores (<2 nm), micropores (2–10 nm), mesopores (10–100 nm), macropores (100–1000 nm), super macropores (1000–10000 nm) and microfractures (>10^4 nm) as previous research [19]. Pore volume and average pore radius with increased temperatures are documented in Table 2. The temperatures of 400 °C and 600 °C create significant changes in the pore structure. When the temperature was lower than 200 °C, few thermal reactions took place. Due to the removal of partial moistures and volatiles, slightly more super micropores and micropores volume was generated. However, pore volume, average pore radius and porosity increased markedly when the pyrolysis temperature reached 400 °C and 600 °C. Between these two temperatures, a large increase was shown in the pore radius and porosity, which means that a strong dilation of the fractures and pores volume took place.

Pore size distribution with temperature can be divided into three stages. The first is the low temperature stage from 25 °C to 200 °C where the total pore volume is relatively low, and the original micro and macro pores are predominant, occupying ~70% of the total. The second stage ranges from 200 °C to 400 °C where all pores increase with increasing temperature. However, the macropore volume increases faster than that of other pore sizes. The macropore content increased from ~20% to 50% from the low to medium temperature stages, which should effectively improve the permeability of specimen. In the last high temperature stage from 400 °C to 600 °C, the micropores volume linearly increased with temperature and they comprised ~35% of the total volume. Although the pores volume for other scale pores also increased with increasing temperatures, the amplitude was relatively less than the micropores. Previous research [34] proved that for low temperature pyrolysis of Yallourn brown coal that the micropore size distribution was not significantly changed, while for high temperature pyrolysis a remarkable increase of the microporosity was observed due to the release of inorganic gases after the tar formation stage.

Fractures are very important to coal permeability, especially for the process of CBM exploitation and coal mining [35–38]. For LRC sample, fractures are less developed, have low density and were characterized by isolated, orthogonal or Y-shaped structures, but with relatively good connectivity and infrequent mineralization. The fractures can be divided into four types based on our previous classification [15,39]: Type A, with width (W) > 5 μm and length (L) ≤ 10 mm; Type B, with W > 5 μm and L ≤ 10 mm; Type C, with W < 5 μm and L > 300 μm; and Type D, with W ≤ 5 μm and L ≤ 300 μm. The fractures evolution along with elevated temperatures is shown in Fig. 5, which shows that the main contribution to the increase of total fractures should be type A and type D. Previous research reveals that temperature can effectively improve the fracture area even when it does not exceed 100 °C [40]. There is a rapid increase for fractures at 300 °C and then the fracture frequency is relatively stable until 800 °C, which means the suitable temperature for enhanced CBM should be in range of 300–800 °C, especially from the perspective of permeability.

3.3.2. Porosity and permeability

Previous research [41] conducted porosity measurements on two subbituminous coals during pyrolysis and obtained porosities of 32.46% at 400 °C, 43.37% at 600 °C and 59.89% at 800 °C, respectively. One Chinese steam coal with the porosity of 22.89% at

![Fig. 5. Area of different type fractures and total fractures with temperatures for LRC sample.](image)

![Fig. 6. Porosity and permeability ratio change with increased temperatures (data of square points [12] and data of round points [43]) during coal pyrolysis.](image)

| Table 2 | Pore structure and Langmuir parameters of equilibrium isotherms (T = 25 °C) of LRC. |
|---------|---------------------------------|-----------------|-----------------|-----------------|
| Sample No. | Sample density (g/cm³) | Pore volume (mm³/g) | Average pore radius (mm) | Langmuir model |
| LRC (25 °C) | 1.39 | 39.2 | 45.3 | 0.995 | 14.13 | 1.69 |
| LRC (200 °C) | 1.41 | 85.7 | 50.6 | 0.992 | 13.56 | 1.79 |
| LRC (400 °C) | 1.47 | 140.5 | 50.8 | 0.993 | 17.81 | 1.07 |
| LRC (600 °C) | 1.53 | 230.4 | 110.6 | 0.996 | 19.45 | 0.79 |
| LRC (800 °C) | 1.57 | 246.8 | 151.7 | 0.991 | 11.93 | 2.06 |
400 °C and 36.69% at 600 °C [12] shows that temperature has the same effect on porosity for different coals, which are also analogous to our measurements. The coal porosity is made up of pores of different sizes over a broad range, up to five orders of magnitude (Fig. 4). The pore size distribution and total porosity of different rank coals at elevated temperatures are illustrated in Figs. 4 and 6a, which show that the transition point of porosity during pyrolysis increases with the increasing coal rank. The porosity of the LRC and MRC samples decreases slightly as temperatures rise from 25 °C to 100 °C, which may be due to thermal expansion. The pyrolysis does not play a role in this period, as the temperature is still far lower than the critical temperature [13]. It then increases quickly from 100 °C to 400 °C due to the remove of partial moisture, volatiles, initial pyrolysis and the significant generation of pores and fractures. Both physical mechanisms and pyrolysis play important roles in this great increase of porosity. The important temperature range for coal pyrolysis is from 400 °C to 800 °C, during which abundant gas and coal tar are released because of the depolymerization and decomposition. This becomes the period for the highest mass loss (Fig. 2). The temperature for transition point of porosity increases following the increasing coal rank, which means that the coals went through strong hypozonal metamorphosis need more energy to depolymerize and decompose organics. Although the escape of the gas or coal tar will produce more pores and fractures and thus cause an increase of its porosity, the sedimentation of the coal tar or other products will occupy some pores and fissures after 700 °C. Thus the maximum temperature for enhancing CBM recovery by partial coal pyrolysis is limited to 700 °C, especially for low-rank coal.

Given the significance of coal permeability, many researchers focus on the permeability of coal and obtained valuable results from both experiments and theoretical modeling [19,35,36,38]. Previous research [42] found an empirical relationship between the meso-pores and the permeability on the basis of the pore structure and permeability of coal during pyrolysis. The relationship between the pores and the permeability without applied stress was evidenced by previous research [43] and phenomenologically divided into three stages: slight fluctuation stage (25–300 °C); exponential increase stage (300–400 °C) and linear increase stage (400–600 °C). The relationship between the pores and the permeability with applied stress was evidenced by previous research [42,43] and phenomenologically divided into two stages (Fig. 6b): exponential decrease stage (25–300 °C) and exponential increase stage (300–400 °C). These two experiments show that stress has a strong impact on coal permeability at the low temperature stage (<300 °C), there is no significant result for high temperatures due to the experimental constraints. To make the permeability under different conditions (with and without applied stress) comparable, the raw permeability data was transferred to be the permeability ratio. These two experiments also show that there is an exponential trend for permeability after 300 °C, which means the pyrolysis has a larger effect on permeability than thermal expansion at the high temperature range, up to 400 °C.

3.4. Methane adsorption

When the coal specimens were heated to 200 °C, some pores such as interconnected pores and pores accessible to gases were easily jammed by the accumulation of volatiles [23] and thermal expansion. Based on the TG–MS experiments, the volatiles should be partially removed before 200 °C, which may effectively decrease the porosity of super micropores and micropores. Thus it could reduce the methane adsorption capacity to 13.56 cm³/g. With the temperature further increased to 400 °C, the moisture and volatiles within the coal matrix escaped and partial organics were pyrolyzed, which effectively increased the pore volume and improved the methane adsorption capacity up to 17.81 cm³/g. Although the LRC (800 °C) has a larger pore volume than other samples at lower temperatures (25 °C, 200 °C, 400 °C and 600 °C), the sample LRC (800 °C) had a lower methane adsorption capacity than others due to the graphitization. Thus the pore structure and the extent of graphitization worked together for the methane adsorption capacity.

The methane adsorption at 25 °C in the pressure range of 0–10 MPa, shown in Fig. 7, was collected by the volumetric method. The uptake of methane drastically increased at relatively low pressures (<1 MPa), but then increased slowly with the pressure further increasing, which was comparable to previous results [15,25]. The Langmuir model fitted the data well and the parame-

![Fig. 7. Comparison of methane adsorption profile obtained by applying the Langmuir model at 25 °C; (a) data of XJD sample [23] and (b) data of LRC sample.](Image)

![Fig. 8. Partial coal pyrolysis model and new generated gas content model for LRC.](Image)
The maximum adsorption volume \( C_0 \) generation is from 300 \( \frac{v}{C_0} \). \( v \) is the new generated gas content (cm\(^3\)/g), and \( m \) is the original gas volume (cm\(^3\)/g). For the LRC sample at different temperatures, the sample LRC (800 °C) showed the lowest methane adsorption capacity of 11.93 cm\(^3\)/g, and the sample LRC (800 °C) with the highest pore volume did not possess the highest methane capacity of 19.45 cm\(^3\)/g. The maximum adsorption volume obtained from the Langmuir model was not only related to the pore structure but also to the extent of graphitization.

3.5. Implication to enhanced coalbed methane recovery

From the experiments, we gain knowledge about the petrophysics development and the pore structure alteration, which results in the variation of methane adsorption capacity and changes in permeability. The roles that pore structure and graphitization play in the methane adsorption of coals under elevated temperatures will lead to a better understanding of the methane adsorption mechanisms of the coals. In addition, such experiments help to establish qualitative and semi-quantitative relationships between the weight loss and the amount of generated gases (Fig. 8), thus providing significant information for methane production from coal seams. Assuming the coal volume is a constant \( C \), the new generated gas content can be calculated by:

\[
GC_{\text{added}} = \frac{v - v'}{m - m'} - \frac{v}{m}
\]

where \( GC_{\text{added}} \) is the new generated gas content (cm\(^3\)/g); \( v \) is the original gas volume (cm\(^3\)); \( v' \) is the new generated gas volume (cm\(^3\)); \( m \) is the original coal weight (g); \( m' \) is the lost weight during pyrolysis (g).

The valuable gases are extracted from the pyrolysis of coals with increasing temperature. Therefore, the crucial factor of the partial pyrolysis is the petrophysics of the coal reservoir and the migration of the produced gases. The major advantage of partial pyrolysis for enhanced CBM recovery is that organics in coal are converted into easily handled gases and become a form of clean energy [4,5]. Coal pyrolysis will occur at a critical temperature; the products including the tars (liquid phases) and gases generated during the process will then permeate into the production wells (Fig. 9).

4. Conclusions

Pore structure, fracture features, permeability and methane adsorption capacity of coal during partial pyrolysis process were investigated to provide the prospective results for enhancing CBM recovery. Multiple methods (including SEM, TG–MS, MIP etc.) were used to study the petrophysical changes accompanying partial pyrolysis. The TG–MS revealed that the main temperature range for CH\(_4\) generation is from 300 °C to 600 °C. Combining the suitable maximum temperature for improving petrophysics of coal reservoir, the most favorable maximum temperature for enhancing CBM recovery should be <700 °C. The pore structure significantly changed and the pore volume was greatly developed with elevated temperatures, especially after 400 °C. Methane adsorption results in partial pyrolysis were well described by the Langmuir model, which demonstrated that the high adsorption capacity of methane was not only related to the pore structure but also to the extent of graphitization. However, many mechanisms of partial coal pyrolysis are still unresolved; more work is therefore needed to provide a better understanding of this phenomenon.

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References

adsorption capacity and flow capability of bituminous and subbituminous

Feng YY, Jiang CF, Liu DJ, Chu W. Experimental investigations on

Luo JJ, Liu YF, Jiang CF, Chu W, Jie W, Xie HP. Experimental and modeling study


Cai YD, Liu DM, Pan ZJ, Yao YB, Li JQ, Qiu YK. Petrophysical characterization of

Tiwaria P, Deo M, Liu CL, Miller JD. Characterization of oil shale pore structure

before and after pyrolysis by using X-ray micro CT. Fuel 2013;107:547–54

Eglinton TI, Larer SR, Boon JJ. Characterisation of kerogens, coals and


Durand-Sournon C, Boulet R, Durand B. Formation of methane and


Potential of thermogravimetric analysis coupled with mass spectrometry for

the evaluation of kerogen in source rocks. Chem Geol 2002;184(3–4):185–94

Tarsaweji YI. Porous structure and adsorption properties of natural porous


Zhao YS, Qu F, Wan ZJ, Zhang Y, Liang WG, Meng QR. Experimental

investigation on correlation between permeability variation and pore

structure during coal pyrolysis. Transp Porous Media 2010;82:401–12

Yu YM, Liang H, Hu YQ, Meng QR. Study of micro-pores development in


Rubel AM, Jagtoven M, Stencel JM, Ahmed SN, Derbyshire FJ. TG-MS for

characterization of activated carbons from coal. In: Symposium on analytical

techniques for characterizing coal and coal conversion products American


Cai YD, Liu DM, Yao YB, Li JQ, Qiu YK. Geological controls on prediction of

coaled methane of No. 3 coal seam in Southern Qinshu Basin, North China.

Int J Coal Geol 2011;88:101–12

Li Y, Lu G, Rudolph V. Compressibility and fractal dimension of fine coal

particles in relation to pore structure characterisation using mercury


Comisky JT, Santiago M, McCollom B, Buddhala A, Newsham KE. Sample size

effects on the application of mercury injection capillary pressure for

determining the storage capacity of tight gas and oil shales. CSUG/SPE

Master Thesis of Taiyuan University of Technology, 2012.

Cai YD, Liu DM, Yao YB, Li JQ, Liu JI. Fractal characteristics of coal pores based

on classic geometry and thermodynamics models. Acta Geol Sin-Engl

2011;85:1150–62

Cai YD, Liu DM, Pan ZJ, Yao YB, Li JQ, Qiu YK. Porose structure and its impact on

CH_{4} adsorption capacity and flow capability of bituminous and subbituminous

coals from Northeast China. Fuel 2013;101:258–68


Luo JI, Liu YF, Jiang CF, Chu W, Jie W, Xie HP. Experimental and modeling study

do methane adsorption on activated carbon derived from anthracite. J Chem

Eng Data 2011;56:4919–26

Lee WH, Park JS, Sok JH, Reucroft PJ. Effects of pore structure and surface state

on the adsorption properties of nano-porous carbon materials in low and high


Feng Y, Jiang CF, Liu DJ, Chu W. Experimental investigations on

microstructure and adsorption property of heat-treated coal chars. J Anal

Appl Pyrol 2013;104:559–66

Karacan CO. An effective method for resolving spatial distribution of

adsorption kinetics in heterogeneous porous media: application for carbon


Pan ZJ, Connell LD, Camilli M, Connelly L. Effects of matrix moisture on gas


Cai YD, Liu DM, Pan ZJ, Yao YB, Li JQ, Qiu YK. Petrophysical characterization of

Chinese coal cores with heat treatment by nuclear magnetic resonance. Fuel

2013;108:292–302


behaviour during the pyrolysis of low rank perthoidal coals. J Anal Appl Pyrol

2003;68–69:371–85

Bae JS, Bhatica SK, Rudolph V, Massarotto P. Pore accessibility of methane and


Li C, Zhao J, Fang Y, Wang Y. Pressurized fast-pyrolysis characteristics of


Liu DM, Yao YB, Tang DZ, Tang SH, Che Y, Huang W. Coal reservoir characteristics

and coalbed methane resource assessment in Huainan and Huaihe coal fields, Southern


Yin CQ, Jiang CB, Wang JC, Xu J. Combined effect of stress, pore pressure and

temperature on methane permeability in anthracite coal: an experimental

study. Transp Porous Med 2013;100:1–16

Niu SW, Zhao YS, Hu YQ. Experimental investigation of the temperature and

pore pressure effect on permeability of coal under the in situ condition. Transp

Porous Med 2014;101:137–48

Charland JP, MacPhee JA, Giroux L, Price J, Kham B. Application of TG-FTR

to the determination of oxygen content of coals. Fuel Process Technol

2003;81:211–21


Liu JS, Chen ZW, Elsworth D, Qu HY, Chen D. Interactions of multiple processes

during CBM extraction: a critical review. Int J Coal Geol 2011;87(3–4):175–89

Pan ZJ, Connell LD. Modelling permeability for coal reservoirs: a review of

analytical models and testing data. Int J Coal Geol 2012;92:1–44

Wang S, Elsworth D, Liu J. Permeability evolution during progressive

deforestation of intact coal and implications for instability in underground


evolution in fractured coal—Combining traxial confinement with X-ray

tomography, acoustic emission and ultrasonic techniques. Int J Coal

Geol 2014;122:91–104

Yao YB, Liu DM. Microscopic characteristics of microfractures in coals: an

investigation into permeability of coal. Procedia Earth Planet Sci

2009;1:903–10

Mathews JP, Pone JDN, Mitchell GD, Halleck P. High-resolution X-ray

tomography observations of the thermal drying of lump-sized


Tomceczek J, Gil S. Volatiles release and porosity evolution during high pressure


Dana E, Skoczylas F. Gas relative permeability and pore structure of


Li MM. The research on pyrolysis-penetration and microstructure of lignite.

Master Thesis of Taiyuan University of Technology, 2012.