Temperature and Deformation Changes in Anthracite Coal after

Methane Adsorption

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Abstract: Micropores are the primary sites of methane adsorption in coal, and the heterogeneous mesostructures of coal create the non-uniform distribution of the micropores in coal. Using a thermal infrared imager, the temperature distribution on the surface of an anthracite sample during methane adsorption/desorption was tested in this paper, and a new method is advanced to calculate methane adsorption capacity in coal based on its temperature increment. The results confirm the strongly non-uniform distribution of methane adsorption in coal. A X-ray CT scan test demonstrates that the volumetric zones of coal sample with a strong methane adsorption capacity have a lower average density. In these regions, the clay minerals with developed micropores also have a strong methane adsorption capacity. During the coal skeleton deformation of methane adsorption, the high density is hard to be squeezed, while low density areas are likely to be squeezed. Therefore, the complexity density distribution in coal leads to the incompatibility of deformation, which make the direct determination of regional uptake a challenge; From the SEM micrographs of the same coal sample with different densities determined by the X-ray CT scan, the mesostructures of cell cavity pores with non-compact packing of the clay minerals appear to be the primary sites of methane adsorption in coal, and the telocollinite with fewer pores has a lower methane adsorption capacity.

Keywords: Cell cavity structure; Vitrinite; Meso deformation; SEM-EDS; Infrared thermal imager; X-ray CT

1. Introduction

Pores are the primary sites of methane adsorption in coal. From the distinction of the pore sizes in a porous adsorbent by Dubinin, the number and specific surface area of the micropores with a pore size less than 2 nm

Nomenclature

$-q$	Isosteric adsorption heat of methane in coal (kJ/mol)
n	The methane adsorption capacity of per unit mass of coal (mol)
Q	The adsorption heat released per unit mass (kJ)
ΔT	The increase in the temperature of the coal ($^{\circ}\text{C}$)
C	The specific heat of coal ($\text{J/kg}\cdot^{\circ}\text{C}$).
$\mu_{i,j}$	The attenuation coefficient of a measured point,
$\rho_{i,j}$	The density of the measured point
μ_m	The ratio constant of the attenuation coefficient.
ρ_0	The density of a certain position of the coal sample before methane adsorption,
ρ_a	The density after methane adsorption.
V_0	Original volume of a certain area of coal sample.

1 directly determine the adsorption capacity of coal. Past studies have evaluated the number and structure of the
2 micropores by MIP (Mercury Intrusion Porosimetry) and N_2 adsorption experiments. However, these studies did
3 not consider the changes in the pore structures during methane adsorption. Recently, X-ray CT (Computed
4 Tomography) scans have been widely used in the research into the mesostructures of coal [1-4]. Compared with
5 the methods of MIP and N_2 adsorption, the methodology of X-ray CT scan has the advantage of studying the
6 mesostructure deformation in coal during methane adsorption to infer the nature of the methane distribution in
7 coal. Karacan et al. have observed and evaluated the differences in gas migration and adsorption rate between
8 different categories of mesostructures using X-ray CT imaging technology, proposed that clay minerals in coal
9 have a high porosity and density, and pore structures in the coal matrix have higher gas storage capacity[5,6].
10 However, during the methane adsorption, the local deformation of coal not under confining stress could be
11 swelling or extrusion deformation [7]. Therefore, the evaluation of the methane adsorption capacity by the

1 variation in the attenuation coefficient of X-ray CT is not sure yet.

2 SEM (Scanning Electron Microscopy) makes use of secondary electron signal imaging to observe the surface
3 morphology of the sample, to infer material components [8], and to reveal the microstructure on the nanometre
4 scale. Many scholars have studied the pore characteristics of coal from different angles via the SEM test, which
5 has multiple advantages in the study of coal pore fissures, mineral matter, and microstructures [9, 10]. Past studies
6 have shown that adsorption heat is released during methane Carbon dioxide and other gases adsorption in coal,
7 resulting in a rise in the coal temperature [11, 12]. The temperature variation during methane adsorption offers a
8 new means to evaluate the methane adsorption/desorption capacity of coal and can also be used as the basis for
9 the prediction of dynamic geological disasters, such as coal seam gas outbursts [13, 14]. The research performed
10 by Chaback et al. [15] shows that methane adsorption in coal is a physical process with heat release, and the
11 temperature variation of the coal is caused by creation of adsorption heat in the process of adsorption. Nodzenski
12 [16] found that under the same conditions, the isosteric adsorption heat of coal and methane increased with the
13 increase of coal metamorphism. If the isosteric heat of adsorption is higher, the adsorption capacity of the coal
14 sample is greater. The experimental study performed by Guo et al. with embedded temperature sensor [17] shows
15 that heat release in coal during CO₂ adsorption is higher than methane, causing the temperature of coal to be
16 increased by 10°C followed by the heat release from methane adsorption, and the heat release from nitrogen
17 adsorption is the lowest. Infrared thermal imager can be used to make multi-point temperature measurements on
18 the surface of an object through the induction of infrared radiation in a colour image display. The infrared thermal
19 imager measurement is a noncontact measurement with many advantages, including fast response, wide range of
20 temperature measurement, high sensitivity, and high space resolution [18]. Liu et al. [19] has successfully
21 observed the temperature change in the coal adsorption/desorption process by using an infrared thermal imager.

22 According to meso mechanics, the meso structures of a material refer to the subtle structures visible through
23 optical or conventional electron microscopy with scales ranging from 10 nm to the millimetre range [20, 21]

1 which mainly refers to the coal matrix, clay minerals and meso pores and fissures in this paper. A suitable
2 observation scale was selected based on the three evaluations (CT, SEM-EDS and infrared thermal imaging).
3 From the SEM-EDS test on the coal sample surface, the original mesostructures of coal can be observed. From the
4 synchronous real-time measurements of X-ray CT and infrared thermal imaging on the same position in the
5 methane adsorption/desorption process, the non-uniformity of mesostructure deformation and methane
6 distribution in coal can be tested under different adsorption pressures. From the combination of the three tests, the
7 deformation characteristics and adsorption capacity of different mesostructures in coal can be analysed, and the
8 diversity of the methane adsorption and the deformation of coal is revealed.

9 **2. Infrared Thermal Imaging Test for Methane Adsorption of Coal**

10 *2.1 Preparation of coal sample*

11 The coal sample for testing is a type of anthracite and was obtained from the Sijiazhuang Coal Mine,
12 Yangquan Coal Industry Group, as shown in Fig. 1. The meso coal sample (12 mm height, 8.5 mm diameter) was
13 cored into the bedding plane. A cross-cut groove was made in the radial direction on the surface of the coal sample.
14 This groove was used as the mark line on the surface of coal sample in different positions. Next, the coal sample
15 was cleaned and dried with oven no more than 60 °C for later use. The results from the measurement of
16 proximate analysis and vitrinite reflectance of the anthracite coal are shown in Table 1.

17 *2.2 SEM and micro X-ray CT scanning test*

18 A JSM-7001F-type thermal field emission scanning electron microscope was used in this paper, with a
19 scanning voltage of 5 kV and a breadth of 10 mm. The microscope could be used to observe the micro structure on
20 the surface of coal on the micrometre scale. For X-ray CT scanning, a μ CT225kVFCB type high-precision micro
21 X-ray CT test system was used [22]. A Uti380D-type high definition infrared thermal imager was used for the
22 infrared scanning test for the methane adsorption of coal, which could be used to detect infrared radiation with a
23 wavelength of 8–14 μ m and with a thermal sensitivity of 0.08 °C. The test principle is shown in Fig. 2. The test

1 system consisted of the following: A pressure cylinder made of titanium alloy material was used for the placement
2 of the coal sample and gas storage and to carry out the adsorption. The test showed that the cylinder had good gas
3 tightness. A transparent infrared glass window was installed on the top of the cylinder and has high infrared
4 transmittance up to more than 95%. A rotation platform was used to fix the pressure cylinder. A digital pressure
5 gauge was used to indicate the pressure of the methane gas in a pressure cylinder. Other auxiliary devices, such as
6 a needle valve, a methane gas storage bottle, and a fixed beam of the infrared thermal imager, and the related
7 tubes and lines were also used. The coal sample was placed in the pressure cylinder vertically and was wrapped
8 with thermal insulation in the axial direction to maintain thermal insulation during the adsorption process. The
9 lower end of the coal sample was supported by a light spring to retain the coal placement during the test. The
10 surface of the upper end was placed in close contact with the highly transparent infrared glass window to aid in
11 infrared thermal imager measurement of thermal radiation. The radiographic source Micro X-ray CT passing
12 through would emit X-rays, and flat panel detector could be used to collect the scanning data. The test device was
13 fixed on the rotation platform of the X-ray CT system, which rotated at a constant speed (the same as the speed
14 used during scanning) to ensure that the coal sample was scanned fully. The displacement of the motion controller
15 for the Micro X-ray CT could be controlled at the micrometre level, and it could ensure that the test device does
16 not shift in any direction during the entire scanning process to ensure the accuracy of the test. The test steps were
17 as follows:

18 1) The coal sample underwent vacuum treatment in the pressure cylinder. A 2XZ-0.5-type double rotary vane
19 vacuum pump was used to take the coal sample to a vacuum less than 0.6 Pa for more than 1 h to ensure that no
20 other gas was present in the coal sample and the pressure cylinder. Manually adjusting focal length of infrared
21 thermal imager caused a radial cross cutting groove on the coal sample to be displayed clearly on the screen of the
22 infrared thermal imager. Then, a photograph of the infrared thermal image and a X-ray CT scan was obtained
23 before the adsorption.

2) Methane gas (99.99%) was used to keep the adsorption pressure at 0.6 MPa. Meanwhile, the infrared thermal imager was used to take continuous photos of the coal sample during methane adsorption, and record the adsorption time until the infrared thermal image remained unchanged. The adsorption was maintained at a constant pressure for 12 h to ensure that the X-ray CT scan was performed at the adsorption state at 0.6 MPa after the adsorption was balanced. Then, the valve was opened, thereby causing a pressure drop to atmospheric. Meanwhile, the infrared thermal imager was used to take continuous photographs of the desorption process of the coal sample and record the desorption time until the infrared thermal image was basically unchanged.

3) The steps of 1) and 2) were repeated. Infrared thermal imaging and X-ray CT scanning were performed for adsorption/desorption process of the coal sample at 1.2 MPa.

3. Methods

3.1 The relationship between temperature and adsorption

The temperature rise of the coal during methane adsorption is caused by the adsorption heat of the coal surface and the methane molecules, which is closely related to the amount of methane adsorption in coal, namely,

$$Q = -qn \quad (1)$$

Assume that the methane adsorption in coal is carried out under adiabatic conditions. As the heat released has no other physical effect but to increase the temperature of the coal, from Eq. (1),

$$n = \frac{\Delta T \cdot C}{\varepsilon} \quad (2)$$

Thus, assuming that the different locations of the coal-specific heat capacity and the isosteric heat of adsorption are constant values, the temperature rise for each coal unit is proportional to its methane adsorption. The higher the rise in temperature, the larger the amount of methane adsorbed.

3.2 The deformation calculation method based on X-ray CT scan

X-ray CT is used to scan the section of the object to be measured by using X-rays to obtain a section image that indicates a change in material density. The attenuation coefficient is the variation in the X-ray intensity when

crossing a section of the measured object, and the relationship between this attenuation coefficient and the density is [23]:

$$\mu_{i,j} = \mu_m \rho_{i,j} \quad (3)$$

The swelling deformation of coal occurred during methane adsorption, resulting in the decrease in the coal density. Therefore, the amount of swelling deformation in the coal can be obtained from its density variation.

If the mass change caused by methane adsorption of the coal is ignored, the following can be obtained:

$$\rho_0 v_0 = \rho(v_0 + \Delta v) \quad (4)$$

Based on the volumetric strain formula, the following expression is obtained.

$$\varepsilon = \frac{\Delta v}{v_0} \quad (5)$$

In Eq. 3, $\Delta V > 0$ means expansion deformation, and $\Delta V < 0$ means extrusion deformation. If Eqs. (1) and (3) are inserted into Eq. (2), the following can be obtained:

$$\varepsilon = 1 - \frac{\mu_0}{\mu} \quad (6)$$

Where μ_0 refers to original attenuation coefficient of a certain position of the coal sample. The parameter μ refers to the attenuation coefficient after methane adsorption. Eq. (4) is based on the computed deformation ε at different positions of the coal sample before and after methane adsorption. If $\varepsilon > 0$, extrusion deformation occurred in this position. Otherwise, expansion deformation occurred in this position.

4. Infrared Imaging Characteristics of Methane Adsorption of Coal

Coal surface temperature arrays at different adsorption/desorption times from the infrared thermal imaging were extracted to compare with the coal surface temperature array before adsorption. A pseudo-colour display in the same colour range was used as the basis for obtaining the change in the coal surface temperature over time under different adsorption pressures. Each pixel of these images corresponds to the absolute size of the coal sample surface $35.4 \times 35.4 \mu\text{m}^2$.

1 The temperature variation during methane adsorption/desorption on the coal surface under 0.6 and 1.2 MPa
2 pressures is shown in Fig. 3. With the increase in the adsorption time, the environmental temperature of the coal
3 sample remained unchanged, and the coal surface temperature rose significantly. During the desorption process,
4 the coal surface temperature decreased. During adsorption/desorption, the coal surface temperature change was
5 non-uniform. The temperature rise during the methane adsorption of the coal first occurred in the right middle and
6 upper area. During desorption, the temperature decrease occurred mainly in the same position. If the adsorption
7 pressure was higher, the temperature changed more significantly. According to 2.1 calculation method, Fig. 3
8 shows that, during the methane adsorption, the right middle region of the coal surface has a larger temperature rise
9 than the adjacent areas, which can be confirmed by its greater methane adsorption. During desorption, desorption
10 of a large amount of methane occurred in this position, thereby causing a more significant temperature decrease.

11 **5. Absorption/Desorption Characteristics of Coals with Different** 12 **Microstructures**

13 The difference in temperature between adsorption and desorption in a rectangular area of the upper right
14 portion of the coal sample (4.5 mm × 2.2 mm) is large. This area was selected for X-ray CT scanning, SEM, and
15 analysis of the temperature change during adsorption/desorption (Fig. 4). SEM results show that the coal sample
16 consists mainly of a vitrinite coal matrix and clay minerals. The telocollinite structure is dense, and pore
17 development is poor. Structural vitrinite contains cell cavity pores and a mesofracture structure on different scales.
18 The distribution of the cell cavity pores is strip-shaped in a certain direction. Clay minerals show bedded
19 crystallization and are packed in a cell cavity pore of the coal matrix or a mesofracture. An energy spectrum test
20 (Table 2) was used. The peak value of the silicon aluminium occurs in this part of the spectrum. This result
21 indicates that its main component is aluminium silicate.

22 A 4.5-mm-wide and 0.075-mm-high rectangular area was selected. ten representative areas with significant
23 characteristics were selected in different radial places on the rectangular. The size of each area was 0.1 mm ×

1 0.075 mm. The SEM analysis was performed at a magnification of 1000 times (Fig. 5). Based on the
2 mesostructures, the area was divided into 4 categories.

3 The first category was a cell cavity pore with non-compact packing of the clay minerals (as the A, B, C, and
4 D areas in Fig. 6). Many 1–20- μ m plant cell cavity tissues are preserved in the coal formation process and
5 partially filled with clay minerals. Due to the squeezing and friction effects of the geological structure, cleats and
6 microfractures (A, B) and breccia (C, D) pores are formed. Due to non-compact packing or long-term erosion,
7 many intercrystalline pores, interlayer holes, and intergranular pores are present in the filled clay minerals.

8 The second category was a cell cavity structure with compact packing of the clay minerals. The E area in
9 Fig. 6 was different from the cell cavity with non-compact packing of clay minerals because this structure was
10 densely filled with clay minerals, and the cell cavity structure was completely preserved. From the SEM image at
11 a magnification of 1000 times, the clay mineral layer is a flake or granular crystal with fewer intercrystalline pores
12 and poor connectivity between cell cavities.

13 The third category is a telocollinite coal matrix. As the F and G areas in Fig. 6, the telocollinite coal matrix is
14 compact and uniform, with almost no meso-scale pore structure at a magnification of 8000 times.

15 The fourth category is a mesofracture filled with clay minerals at different packing degrees. As shown in the
16 H, I, and J areas in Fig. 6, in mesofractures (width of 0–20 μ m), clay minerals are partially or fully filled, thereby
17 forming clay mineral ribbons across various scales.

18 Temperature change curves of different mesostructures in the adsorption/desorption process are shown in Fig.
19 6. During methane adsorption, the temperature rise in the non-compact-packing cell cavity pore (area B) and the
20 fracture structure (area I) with stronger methane adsorption capacity is faster (within 0–10 s), reaching 3.51°C
21 under an adsorption pressure of 1.2 MPa. Within 10–75 s, due to heat transfer and heat dissipation, the
22 temperature decreased significantly. The temperature rise in a compact-packing cell cavity pore (area H) and
23 telocollinite (area F) with a stronger methane adsorption capacity is slower, reaching 2.7°C within 0–20 s. The

1 temperature rises slowly to 2.7°C in 0–20 s of adsorption time. The temperature rise in the compact-packing cell
2 cavity pore (area E) and the telocollinite (area G) with stronger methane adsorption capacity is slowest, reaching
3 2.5°C within 0–43 s. In the desorption process, the region (area B, area I) with the strongest adsorption capacity is
4 preferentially desorbed with the fastest temperature decrease. The region (area E, area F) with the lowest
5 adsorption capacity is preferentially desorbed with the slowest temperature decrease. Because of heat transfer, the
6 temperature of different adsorption areas tends to be balanced for a long time in both adsorption and desorption
7 processes.

8 From the comparison of Fig. 4–6, due to the restrictions of the image resolution, only the density of the coal
9 in a certain area can be estimated by the X-ray CT attenuation coefficient, while the mesostructure of coal,
10 especially the micropores, cannot be described. From Fig. 4, the B area corresponds to the clay mineral cluster
11 with an attenuation coefficient far higher than other areas. Meanwhile, a higher temperature rise than in the
12 adjacent areas occurs during the methane adsorption. In Fig. 5, the B area has developed pore structures,
13 suggesting that the porous clay minerals in the coal have a large methane adsorption capacity. Compared with the
14 area B, the area C is also a porous area with a lower attenuation coefficient. Area C has a temperature rise similar
15 to the area B during methane adsorption, which suggests that its methane adsorption capacity is similar to the area
16 B. As the position of the area A is near the edge of the sample, its temperature rise may be affected by the heat
17 transformation; therefore, it is not discussed in this study. From the comparison of B, C, and D areas, the porous
18 coal matrix and small clay mineral particles have similar methane adsorption capacities.

19 From comparison of C, D, and F areas with similar attenuation coefficients, the C, D areas are located in the
20 mineral ribbons containing clay, with clay mineral particles and developed pores, and the F area is mainly the
21 telocollinite. During methane adsorption, the methane adsorption capacity of the C, D areas is larger than the
22 methane adsorption capacity of the F area, indicating that the micropores are the main sites of methane adsorption.

23 5. Deformation Characteristics of Different Mesostructures of Coal

The X-ray CT scan and deformation characteristics of different mesostructures of coal during methane adsorption are summarized in Table 3. The cell cavity pores non-compactly filled with clay minerals with high methane adsorption capacity (A, B, C, D) can occur with either swelling deformation or extrusion deformation. Even in some areas, the transition from the extrusion to the swelling deformation occurs with the increase in adsorption capacity. The non-coordinated deformation is the main reason for the irreversible damage in coal.

With the clay minerals non-compactly filled, the mesofractures in areas I and J in Fig.5 show extrusion deformation due to the swelling deformation of the surrounding coal during methane adsorption. The mesofracture with clay minerals non-compactly filled in area H has a smaller methane adsorption capacity than the mesofracture with the clay minerals non-compactly filled. However, swelling deformation occurs during methane deformation at its higher extent.

The telocollinite (the areas F and G) is a major component of the coal, but it is not the main site of methane adsorption from the thermal imaging. Either swelling deformation or extrusion deformation can occur during methane adsorption. Even in some areas, the transition from the extrusion to the swelling deformation occurs with the increase in adsorption capacity.

From the comparison of the deformation and the temperature rise in areas B and E, under the pressure of 0.6 MPa, the swelling deformation of E is 1.297 times the swelling deformation of area B, while the temperature rise in E is 0.389 times the temperature rise in area B. From Eq. (2), the methane content of area B is 2.75 times the methane content of area E. Under the pressure of 1.2 MPa, the swelling deformation of F is 5.35 times the swelling deformation of area B, while the methane content of area B is 2.29 times the methane content of area E from the temperature variation. Therefore, it make the direct determination of regional uptake according to the data obtained from the X-ray CT scan a challenge, and this inference occasionally produces incorrect results.

Expansion deformation from the methane adsorption of coal occurred mainly in high-density areas that contain clay minerals. Intercalation adsorption of methane in the clay minerals will cause an increase in the crystal

1 layer spacing of clay minerals [24-26], thereby leading to expansion deformation. A certain degree of extrusion to
2 the adjacent low-density vitrinite coal matrix and pore fracture was observed, causing damage to the coal. The
3 localized density changes in the coal depend on the complex mesostructures and their deformation, which cannot
4 be the evidence of the methane content.

5 **6. Conclusions**

6 With the combination of X-ray CT scanning, SEM-EDS, infrared imaging, and a variety of testing methods,
7 the temperature change and the deformation law for the microstructure in the process of coal adsorption and
8 methane desorption were studied. The study's conclusions are the following:

9 1) Methane adsorption at different positions in the coal had nonuniform adsorption characteristics. During
10 methane adsorption/desorption, the temperature rise/decrease was more obvious in the position where methane
11 adsorption was higher in the coal than in adjacent areas.

12 2) The methane adsorption capacity of coal in different positions was closely related to its mesostructure.
13 In the vitrinite in the coal, a large number of breccia holes and cracked coal structures with different sizes of cell
14 cavity filled with clay minerals, and the mesofracture had a very strong methane storage capacity, and these
15 properties are sensitive to the temperature during adsorption/desorption. In compact telocollinite and
16 compact-packing cracks and cell cavity structures, the pore structure was developed more poorly, and the methane
17 adsorption capacity was weaker. The temperature change was lower during adsorption/desorption.

18 3) Methane adsorption leads to significant deformation of the coal mesostructure. The deformation includes
19 expansion and extrusion deformation. If the adsorption pressure was high, the deformation of the mesostructure
20 increased in significance. Expansion deformation of the coal during methane adsorption occurred mainly in the
21 area containing high-density clay minerals, where a significant squeezing effect was observed on the low-density
22 vitrinite coal matrix and pore and crack structure in the coal.

23 4) During methane adsorption, the localized density changes in the coal depend on the complex

1 mesostructures and their deformation. The localized density changes in the coal have nothing to do with the
2 methane adsorption capacity. Therefore, it is extremely unreliable to infer the distribution of methane in coal
3 according to the data obtained from X-ray CT scan.

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Table 1 Proximate analysis and Vitrinite reflectance of the Anthracite Coal

Rank	Weight (g)	Maximum reflectance of vitrinite (%)	Proximate analysis			
			Moisture (%)	Ash yield (%)	Volatile matter (%)	Fixed Carbon (%)
Anthracite	0.966	2.45	1.39	13.13	7.12	78.36

Table 2 Energy spectrum analysis result of coal surface

Region		Vitrinite matrix			Clay minerals			
EL		C	O	S	C	O	Si	Al
Norm. C [wt.%]		86.36	13.22	0.42	45.67	34.86	10.54	8.93

Table 3 Deformation characteristics of methane adsorption in different meso structure

Mesostructural Region		0 MPa		0.6 MPa		1.2 MPa		
		μ	ε (%)	Type of deformation	$\Delta T_{\text{Ads}}^{9\text{s}}$	ε (%)	Type of deformation	$\Delta T_{\text{Ads}}^{9\text{s}}$
A cell cavity pore with noncompact packing of clay minerals	A	0.005958	23.1361	Extrusion	2.3057	16.7562	Extrusion	3.0066
	B	0.010984	-1.98730	Swelling	1.8217	-5.28148	Swelling	3.3930
	C	0.007078	2.87350	Extrusion	2.9273	3.22974	Extrusion	3.3201
	D	0.006098	2.99946	Extrusion	3.1632	-1.75511	Swelling	3.4497
A cell cavity structure with compact packing of clay minerals	E	0.815000	-25.7660	Swelling	0.7071	8.24077	Extrusion	1.3911
A telocollinite coal matrix	F	0.007134	-7.84819	Swelling	0.5835	-28.2484	Swelling	1.4831
	G	0.007706	-2.13738	Swelling	1.1994	0.08003	Extrusion	2.2567
Filled crack with clay minerals	H	0.011195	-3.63453	Swelling	1.0312	-6.90756	Swelling	2.3302
Filled crack with compact packing of clay minerals	I	0.007699	2.88890	Extrusion	1.6787	8.33720	Extrusion	2.9313
	J	0.005491	13.7046	Extrusion	3.0598	16.3615	Extrusion	3.2086

Nttes: $\Delta T_{\text{Ads}}^{9\text{s}}$ ----is the temperature of the coal at 9s after adsorption

Fig. 1 Coal sample for test

Fig. 2 Test principle of methane adsorption of coal by Micro CT and infrared thermal imager

Fig. 3 Temperature change of coal adsorption/desorption methane captured by infrared thermal imager (°C) (Adsorption time is in white, desorption time is in red)

Fig. 4 CT and SEM image of coal and temperature distribution of methane adsorption/desorption (a, SEM micrographs of coal; b, X-ray CT image of coal c, Attenuation coefficient of rectangular regions; d, Temperature variation of rectangular regions during methane adsorption; e, Temperature variation of rectangular regions during methane desorption)

Fig. 5. SEM micrographs of mesostructure of coal sample shown in Fig.4

Fig. 6 Temperature change of different meso structure of coal during methane adsorption/desorption under 1.2 MPa