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Uniformity of temperature variation in coal during methane adsorption

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ABSTRACT

Uniformity of methane adsorption by coal is important for assessing both the maximum storage capacity and damage caused by nonuniform thermal expansion. Therefore, this study examines the structural characteristics and temperature variation on the surface of coal during methane adsorption at 1 and 1.5 MPa. The results showed that the temperature increase in different surface regions associated with methane adsorption obeys the normal distribution law, and it is closely related to its meso-structure characteristics. That is, the vitrinite of the coal matrix has a fast adsorption rate and a better developed microscopic structure, resulting in a higher adsorption capacity and more pronounced temperature rise. In contrast, clay minerals present in coal have a lower methane adsorption capacity and slow adsorption rate, resulting in a smaller temperature rise.

1. Introduction

Coal is a natural adsorbent that releases heat during methane adsorption, leading to an increase in temperature (Zhao et al., 2012; Li et al., 2010) that can be used to not only evaluate its methane adsorption/desorption capacity, but also predict dynamic geological disasters such as coal gas outbursts (Lu et al., 2015; Yang and Nie, 2015). Chaback and Morgan (1996) showed that temperature variation in coal is mainly caused by the heat of exothermic adsorption; however, Adam (1998) later revealed that the isosteric adsorption heat increases with increasing metamorphism of the parent coal under a given set of experimental conditions. Thus, the greater the adsorption heat, the stronger the adsorption ability of the coal sample. Guo et al. (2000) have shown that the CO_2 adsorption by coal releases the most heat, leading to a 10 °C temperature rise in coal samples, and though methane adsorption releases less heat, it is nitrogen adsorption that releases the least amount of heat. Liu et al. (2015) have suggested that the rise in coal temperature during CO_2 adsorption can reach 0–8 °C, and that the higher the adsorption pressure, the greater the increase in temperature. However, in most of these experimental studies, only single-point contact measurements were used to evaluate the temperature of coal, and therefore, these studies failed to obtain detailed information regarding temperature variation at different positions within the same coal sample.

Past studies have shown that the diversity of macerals, variation in mineral composition, and uneven distribution of pores and fractures in coal create inhomogeneous methane adsorption characteristics (Feng et al., 2016; Zhou et al., 2015), making it necessary to explore the meso-scale temperature variation. Analysis of the surface morphology of coal by scanning electron microscopy (SEM) can differentiate between regions of different composition and reveal the microstructure of the material surface (Cai et al., 2011; Kutchko et al., 2013), while computed tomography (CT) scanning can nondestructively detect internal structures using the difference in X-ray absorption between materials of different density (Karacan and Okandan,2001; Karacan and Gareth, 2003). This latter technique has been used by Wang et al. (2013) to evaluate the internal structure of anthracite coal samples. Infrared imaging spectrometry can also be used to obtain multipoint, noncontact temperature measurements of an object's surface with a high sensitivity, fast response, and high spatial resolution over a wide range temperature range (Abdul et al., 2016). This approach was used by Liu et al.

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(2013) to test the temperature variation in coal during gas adsorption and desorption. In the present study, the temperature variation of coal during methane adsorption is explored through a combination of CT scanning, SEM, and infrared imaging. This is aimed at revealing the mechanism by which methane is stored in coal so as to better understand the damage caused by nonuniform thermal expansion.

2. Infrared thermal imaging of methane adsorption in coal

2.1. Coal sample preparation

The anthracite coal used for these experiments was obtained from the Sijiazhuang mine (Yangquan Coal Industry Group, Shanxi, China). After machining to a size of Φ8.5 × 12 mm, a line was cut across the radial surface of coal sample to provide a position coordinate axis (Fig. 1) so that specific locations on the coal sample surface can be accurately identified during meso-scale CT scanning, SEM, and infrared thermal imaging. Before testing, the coal sample were cleaned and dried. Basic information for coal sample is provided in Table 1.

2.2. Micro-CT and SEM scanning

Rock density is one of the most basic physical parameters of a rock, and has a close relationship with other physical and mechanical properties such as its strength, porosity, and deformation characteristics (Karacan and Okandan, 2001). In CT scanning, the attenuation coefficient is the variation in X-ray intensity when crossing a section of the measured object, and the relationship between this attenuation coefficient and density is (Karacan and Gareth, 2003):

$$\mu_{i,j} = \mu_m \rho_{i,j} \tag{1}$$

Here, $\mu_{i,j}$ is the attenuation coefficient of a measured point, $\rho_{i,j}$ is the density of the measured point, and μ_m is the ratio constant of the attenuation coefficient. Thus, real information about the inner structure of a coal sample can be obtained by using Eq. (1) to transform the gray images obtained of the attenuation coefficient.

A micro-CT system (μCT225kVFCB) installed at the Taiyuan University of Technology was used in this experiment (Yu et al., 2010.); the scanning parameters used are shown in Table 2. JSM-7001F heat field emission SEM at the Chinese Academy of Sciences, Institute of Coal Chemistry (Shanxi, China), was also adopted in this experiment using a scanning voltage of 5 kV and a scan width of 10 mm. Both the CT and SEM data were processed by programs based on Matlab software.

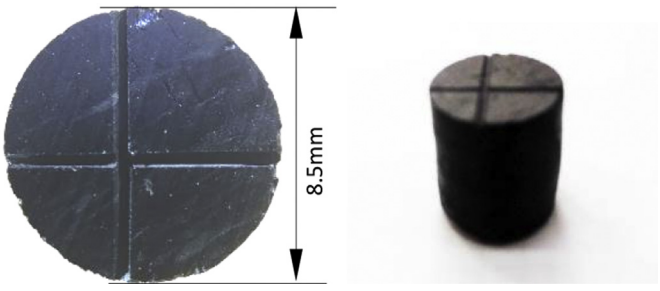

Fig. 1. Machined coal sample for testing.

2.3. Infrared imaging of methane adsorption in coal

The thermal motion of molecules in any object above absolute zero (−273.15 °C) emits infrared radiation, with the relationship between the radiation energy density and temperature of an object obeying the radiation law (Abdul et al., 2016):

$$E = \sigma\varepsilon\left(T^4 - T_0^4\right) \tag{2}$$

where E is the radiation intensity, w/m^3; σ is the Steven-Boltzmann constant (5.67 × 10^{-8} W/m^2, K^4); ε is the infrared radiation rate of the object; T is the temperature of the object (K); and T_0 is the temperature of the surrounding environment (K). Using the infrared radiation energy measured by an infrared detector and optical imaging lens, an infrared thermal imager can be used to display images of an object's surface that can be used to calculate its temperature array based on Eq. (2).

A Uti380D infrared thermal imager was used for infrared scanning of methane adsorption in coal at a wavelength of 8–14 μm, with a thermal sensitivity of 0.05 °C. As shown in Fig. 2, this system consists of the following parts: (1) A pressure cylinder made of titanium alloy to place the coal and gas for carrying out the adsorption in coal; the alloy was tested and confirmed to have good air tightness. A piece of glass with a high transmittance (>90%) of infrared was positioned at the top of the cylinder. (2) A base was used to fix the cylinder clamping device to the infrared thermal imager, thereby ensuring stability of the scanned infrared images. (3) A precision digital pressure gauge for measuring the pressure of methane in the cylinder. (4) A gas injection device incorporating a pressure reduction valve, methane cylinder, and corresponding pipeline. Testing was accomplished by first placing coal samples horizontally in the cylinder so that their radial surface was close to the high-transmittance infrared glass and therefore visible to the infrared thermal imager. Experiments were then carried out at a constant temperature of 15 °C as per the following procedure:

1) In order to reduce heat loss from the coal during methane adsorption and eliminate the influence of environmental temperature factors, the side surface of the coal sample was wrapped with insulating cotton to keep it as adiabatic as possible. The clamping device was then adjusted and fixed to ensure that the coal sample was parallel to the detector shot of the infrared thermal imager in the cylinder. Using a 2XZ-0.5 double rotary vane vacuum pump, a pressure of 0.6 Pa was produced in the cylinder for more than 1 h to remove all gases from the coal sample and the cylinder.
2) The focal length of the infrared thermal imager was manually adjusted so that the cross-cut groove on the sample's surface could be clearly seen, and then, a reference shot was taken of the coal surface before methane adsorption.
3) The pressure reduction valve was opened and methane gas (99.99%) was injected at two different times to maintain constant pressures of 1 and 1.5 MPa, respectively, in the cylinder while simultaneously recording the adsorption time. Infrared thermal images were observed in real time for more than 20 min, and the experiments were stopped once the infrared thermal images were stable.

3. Temperature variation of coal during methane adsorption

3.1. Adsorption heat theory

Coal has an organic macromolecular structure that consists of a three-dimensional cross-linked network in which a large number