Pore structure and its impact on susceptibility to coal spontaneous combustion based on multiscale and multifractal analysis

Zhang Yu1,2, Zhang Xueqing1, Yang Wen1,3, Xin Haihui4, Hu Sherong1,2 & Song Yu2,3

The relationship between the properties of coal and its tendency to spontaneous combustion is critical for the environment, safety concerns, and economy. In this study, to eliminate the complex influence of moisture, the samples having similar moisture content were selected from Shanxi and Henan provinces. The chemical properties, physical properties, and tendency of coal samples to spontaneous combustion were characterized based on the conventional analysis, mercury intrusion porosimetry, fractal dimensions, and crossing point temperature (CPT). The results confirmed that the coal rank, volatile matter, oxygen contents, and fixed carbon content had a good linear relationship with the CPT. The relationship between the ash content and CPT presented a “U-shaped” non-linear correlation. For the pore size distribution, the total pore volume also possessed a linear positive correlation with the CPT. The fractal curves could be distinctly divided into two stages: low-pressure (<20 MPa) and high-pressure (>20 MPa), from which the fractal dimensions were obtained using the Sponge and Sierpinski models. The relationship between the fractal dimensions (D1, D2, and Dg) and CPT could be divided into two distinct stages: a decrease in the CPT with increasing fractal dimensions (2.6–2.85), and then an increase in the CPT. CPT decreased with increasing parameters of D1, D2, H, and Dg, and it gradually increased with increasing D10, D20, D10-Dg, and Dg-D10. The above characteristics are important to comprehensively and systematically reveal the mechanism of spontaneous combustion.

Low temperature (i.e., <200 °C) chemical and/or physical processes in fossil fuels result in the accumulation of heat, which thereby leads to spontaneous combustion1,2. Numerous problems are caused by spontaneous combustion of coal, such as environment issues (emission of greenhouse gases, toxic and harmful gases, and trace elements)3-4, safety concerns (dust and gas explosions, unstable overlying rocks, large cracks, and subsidence)7-9, and economical loss (destruction of apparatus and equipment, and loss of coal resources)3,10. Therefore, it is important to evaluate the degree of proneness for the prevention of the spontaneous combustion of coal.

The crossing point temperature (CPT) is an index to evaluate the tendency of coal to spontaneous combustion11-13. Coal properties, oxygen, and ignition are three main factors for predicting the spontaneous combustion tendencies of different coals in chemical and/or physical processes14. Numerous studies have been reported on the intrinsic properties of coal and its spontaneous combustion tendency15-20. Qi et al.21 analyzed the relationship between the CPT and moisture, coal rank, and sulfur content. Nimaje and Tripathy22 demonstrated that the parameters of the ultimate analysis had a significant correlation with the Olpinski index, and this relationship could be used as a reliable index to assess the susceptibility of Indian coals to spontaneous combustion. Chandra and Prasad23 found that low coal horizons (less than 36% V.M.; Romax. 0.90–1.25%) were least susceptible to spontaneous combustion. Pattanaik et al.24 demonstrated that the intrinsic properties of coal (stratigraphy or coal rank, volatile matter, and petrography) had a good relationship with the susceptibility indices of spontaneous combustion (CPT, and differential thermal analysis/DTA). Nimaje et al.13 analyzed the statistical relationship

1College of Geoscience and Surveying, China University of Mining & Technology, Beijing, 100083, China. 2Key Laboratory of Coalbed Methane Resource & Reservoir Formation Process, Ministry of Education, China University of Mining & Technology, XuZhou, 221116, China. 3School of Earth Science and Engineering, Hebei University of Engineering, Handan, 056038, China. 4School of Safety Engineering, China University of Mining & Technology, Xuzhou, 221116, China. *E-mail: hsr8516@126.com; songyu1009488@126.com
between the CPT and the proximate analysis parameters, and found that mixture surface regression (MSR) model was more effective in predicting spontaneous heating liability of coal.

The influence of water on the self-heat process is complex. Moisture can accelerate the oxidation, and enhance the thermal response by hindering the formation of stabilized radicals. However, the liability of spontaneous combustion of air-dried coal samples increases in the moisture content. Zhang et al. and Qi et al. found that moisture may play a role in slowing down spontaneous combustion.

Several pore classification standards have been proposed, which are as follows: 1) Hoxter classified pores into micropores (<10 nm in diameter), transitional pores (10–100 nm), mesopores (100–1000 nm), and macropores (>1000 nm); the International Union of Pure and Applied Chemistry (IUPAC) has classified pores into micropores (<2 nm), mesopores (2–50 nm) and macropores (>50 nm); and Yao et al. classified pores into adsorption pores (<100 nm) and seepage pores (100 nm).

Pore structures play an important role in the combustion and oxidation of coal. Pores provide a good pathway to the transport oxygen to coal surface at low temperature, which increases consumption of oxygen. Small space or volume can improve the material performance. Karsner and Perlmutter found that coal with a large pore volume had high oxidation rate. Parsa et al. evaluated the effect of densification on brown coal on its physical properties and spontaneous combustion propensity. The results exhibited that the decrease in micropore volume led to a decrease in the contact between oxygen and the coal surface, thereby increasing the critical ignition temperature. Air can more easily contact the macropore structures of coal (the decreased in the reactivity is initially rapid) than the micropore structures. Mainly investigations on coal structural characteristics such as the pore volume, surface area, pore size distribution, and heterogeneity are conducted to reveal the spontaneous combustion.

Pore structure characteristics have been widely applied in Coalbed Methane (CBM) exploration and exploitation, shale gas reservoirs, and predicting favorable zones. Mono fractal approaches have been extensively used in investigating the fractal characteristics of pore structures. However, a single-scale (mono-fractal) analysis or a single fractal dimension cannot explain the differences in the pore size intervals and types of erratic variation or local variation that occur in the inner distribution of pore sizes. Therefore, a multi-scale fractal model is used for different coal ranks, and tectonically deformed coals with the same coal rank. Besides, multifractal methods are also used for non-homogeneous porous media to reveal the heterogeneous pore characteristic. Li et al. and Song et al. conducted a the multifractal analysis to investigate the variability and heterogeneity of tectonically deformed coals by high-pressure mercury intrusion experiment. Therefore, multifractal analysis is an efficient method to investigate pore size distribution. Nevertheless, focus on the relationship between the spontaneous combustion characteristics and heterogeneity in different coal ranks is lacking.

The objective of this study was to develop an understanding of the relationship between the properties of coal and its tendency to spontaneous combustion. The experiments were conducted by conventional analysis, mercury intrusion porosimetry, and CPT. To eliminate the complex influence of moisture in the process of spontaneous combustion, coal samples having similar moisture contents were selected. This was done to reveal the coal intrinsic properties (coal rank, volatile matter, oxygen contents, fixed carbon contents, and sulfur content), pore characteristics (pore volume, surface area, pore size distribution, and heterogeneity), and tendency of coal to spontaneous combustion. Both multiscale and multifractal methods were used to systematically investigate the heterogeneity and susceptibility to coal spontaneous combustion. Such research is important to comprehensively and systematically reveal the mechanism of spontaneous combustion.

**Experiments and Modelling**

**Geological setting.** A total of seven coal samples were collected from Shanxi and Henan provinces (Fig. 1), which contain the major coalfields in China. Six samples were collected from three coalfields in Shanxi, including Ningwu, Xishan, and Qinshui, and one sample was collected from Henan coalfield (Pingdingshan). The main coal-bearing stratum of these coalfields belongs to the Carboniferous–Permian system. Samples were directly collected from coal colliery following the Chinese Standard Method GB/T 19222–2003 and were carefully packed and taken to the laboratory for experiments.

**Samples and experiments.** Seven coals were collected from Ningwu, Dongqu, Guandi, Longle, Fenghuan, and Pingdingshan collieries in Shanxi and Henan provinces. The coal samples were crushed to −200 meshes (~0.074 mm) and vacuum-dried. The ultimate analysis and proximate analysis were conducted in accordance with the Chinese national testing standards (GB/T 212–2008 and GB/T 31391–2015). Vitrinite random reflectance (%Rr) were measured for all the coal samples on the same polished sections using a Leitz MPV-3 photometer microscope, following conventional methods in accordance with the Chinese national standard (GB/T 6948–1998).

The CPT measurements were conducted at the China University of Mining and Technology. The details of the experiment are reported in our previous work. The samples (mass 50 g with a particle size of ~0.18–0.43 mm) were exposed to a dry air flow of 50 mL/min within the reactor with a temperature ramp rate of 1 °C/min with coal and oven temperatures being recorded. When the coal temperature is equal to the oven temperature, the sample is at the CPT.

The coal samples were prepared by a vacuum drying for 12 h at 70–80 °C. High pressure mercury injection (HPMI) experiment was performed for the samples using an Auto Pore IV 9501 HPMI instrument at the China University of Mining and Technology. The mercury injection pressure ranged from 0.90 to 4.0 × 10^6 PSIA. The pore diameters obtained were from 5.35 to 2.28 × 10^5 nm.

**Fractal dimensions.** Based on the Sierpinski model, the fractal dimensions (D_s) can be calculated by the following equation:
\[ \ln(V) = (3 - D_s)\ln(P - P_t) + \ln(\alpha) \]  

where \( V \) is the mercury injection amount at \( P \) in mL, \( D_s \) is the volume fractal dimension, \( P_t \) is the mercury inlet pressure in MPa, and \( \alpha \) is a constant. If the slope of the \( \ln(P - P_t) \) vs. \( \ln(V) \) curve is \( K \), then \( D_s \) is \( 3 - K \).

**Sponge model.** Based on the Menegr model, the fractal dimensions (\( D_g \)) can be calculated by the following equation:

\[ D_g = \ln[\frac{dV(r)}{dP(r)}] - \ln(\alpha)\ln(P(r)) + 4, \]

where \( V_{P(r)} \) is the cumulative injection volume at a given pressure \( P(r) \) and \( \alpha \) is a constant. Therefore, the pore fractal dimension, \( D_p \), can be obtained by: \( D_p = 4 + A \), where \( A \) is the slope in Eq. (2).

**Multifractals.** Multifractal analysis is used to measure the statistic Hg pore size distributions. The pore diameter interval (\( I \)) ranging from 0.006 nm to initial diameter (responding to the least pressure) was selected to generate a box \( N(\epsilon) = 2^k, \epsilon = L \times 2^k \) by dyadic partitions in \( k \) stages \( (k = 1, 2, 3, \ldots) \), where \( L \) is the length of the support. The probability, \( P_j(\epsilon) \), of the pore size can be calculated as:

\[ P_j(\epsilon) = \frac{N_j(\epsilon)}{N}, \]

where, \( N_j(\epsilon) \) is the volume of a box \( (j=1, 2, 3\ldots) \), and \( N \) is the total volume of the system. The probability for each box of size \( \epsilon \) unit can be calculated as.
\[ P(\varepsilon) = \varepsilon^{-\alpha_j}, \]  
(4)  

where \( \alpha_j \) is the coarse Hölder or singularity exponent for the boxes, which theoretically represents how the singularities of a system tend to infinity in the limit \( \varepsilon \to 0 \).

The \( \alpha \) exponent, \( N_\alpha \), was used to evaluate the number of boxes, as follows:

\[ N_\alpha(\varepsilon) = \alpha^{-f(\alpha)}, \]  
(5)  

where the set of \( f(\alpha) \) values represents the spectrum of fractal dimensions that characterize the abundance of the set of points with singularity \( \alpha \). \( f(\alpha) \) can be calculated as \(^4^8\):

\[ f(\alpha) \propto \sum_{j=1}^{N(\varepsilon)} u_j(\varepsilon) \log(p_j(\varepsilon)) \]  
(6)

and

\[ f(\alpha(q)) \propto \sum_{j=1}^{N(\varepsilon)} u_j(\varepsilon) \log(u_j(\varepsilon)) \]  
(7)

where \( \mu_j(q, \varepsilon) \) and \( P_j(\varepsilon) \) are the normalized measures, defined as \(^4^8\):

\[ \mu_j(q, \varepsilon) = \frac{p_j^\alpha(\varepsilon)}{\sum_{j=1}^{N(\varepsilon)} p_j^\alpha(\varepsilon)} \]  
(8)

\[ \chi(q, \varepsilon) = \sum_{j=1}^{N(\varepsilon)} p_j^\alpha(q, \varepsilon) \]  
(9)

where \( \chi(q, \varepsilon) \) can be calculated as:

\[ \chi(q, \varepsilon) \propto \varepsilon^{-\tau(q)} \]  
(10)

where \( \tau(q) \), \( q \)th mass exponent, can be defined as \(^4^8\):

\[ \tau(q) = \lim_{\varepsilon \to 0} \frac{\log \mu(q, \varepsilon)}{\log \left( \frac{1}{\varepsilon} \right)} = (1 - q)D_q, \]  
(11)

where \( D_q \) called the generalized fractal dimensions or Rényi dimensions can be calculated as \(^4^8\):

\[ D_q = \frac{1}{q} \lim_{\varepsilon \to 0} \frac{\log \mu(q, \varepsilon)}{\log \varepsilon} (q = 1), \]  
(12)

\[ D_1 = \frac{\sum_{j=1}^{N(\varepsilon)} p_j^\alpha \log p_j}{\log \varepsilon} (q = 1), \]  
(13)

**Results and data analyses**

**Conventional characteristics.** The vitrinite random reflectance (Rr, %) of the coal samples was ranged from 0.58% to 3.43%, corresponding to medium-rank coal (bituminous coals A, B, C, and D) to high-rank coal (anthracite coals B and C) (ISO 11760, 2005)\(^5^4\). Proximate analysis showed that the volatility of the coals varied from 5.95% to 43.45%. The moisture content was similar in different coal ranks. The fixed carbon ranged from 27.83% to 80.88%. The total sulfur content changed from 0.42% to 9.36%. The ash yields also had a wide range, varying from 5.47% to 49.09% (Table 1).

**Macropores structure from HPMI experiments.** Pore structure distribution. Table 2 lists the pore parameters obtained from the HPMI. In this study, the classification standards defined by Yao \textit{et al.}\(^2^8\) and the sharpness of the curve were used. The following three ranges are present: \( V_1 < 100 \) nm, \( 100 < V_2 < 1000 \) nm, and \( V_3 > 10000 \) nm. Samples S1 and S2 have the largest and smallest cumulative pore volume in \( V_3 \), respectively. Cumulative pore volumes \( V_1 \) have a relatively lower distribution than \( V_2 \) or \( V_3 \), and among the samples, sample S1 has the highest distribution. The coal rank ranges from bituminous A to anthracite B when the cumulative pore volume, \( V_3 \), is the same (0.002 cm\(^3\)/g). Samples S1 and S3 have the smallest and largest cumulative pore volumes \( V_3 \), respectively, which are in response to the total pore volume.

The mercury injection and withdraw curves as well as the pore size distribution are shown in Fig. 1\( \text{a,b} \), respectively. For the high-rank coals, the mercury intrusion and extrusion curves (Fig. 2\( \text{a} \)) display a similar trend (parallel type), indicating the dominance of the parallel plate pores and a good connectivity for gas diffusion. The shape increases in case of mercury intrusion at low pressures reveal a high proportion of \( V_3 \), and the slightly straight lines reveal a poorly developed \( V_1 \), which are in agreement with pore volume distribution. For the medium-rank coals,
there is larger space between the mercury intrusion and extrusion curves (hysteresis loop) (Fig. 2a) than between those of the high-rank coals (tip-edge type), indicating a larger V₁, small V₂ and V₃, and poorer pore connectivity than that in the high-rank coals. The larger hysteresis loop suggests a significant existence of the semi-closed pores.

The pore size distribution curves (Fig. 2b) remarkably change with the increase in the coal rank.

Fractal dimensions by Sierpinski model. The fractal curves based on the Sierpinski model are presented in Fig. 3. Fractal dimension Dₛ₁ and Dₛ₂ are obtained in low-pressure (<20 MPa, responding to the see page pores, >100 nm) and high-pressure (<20 MPa, responding to adsorption pores, <100 nm) stages. The correlation index of Dₛ₁ ranges from 0.30 to 0.99. Medium-rank coals S₁, S₂, S₃, and S₅ and high-rank coal S₅ present a better correlation. However, the correlation index of Dₛ₂ had a high correlation index (0.80–0.995). The values of Dₛ₁ and Dₛ₂ ranges from 2 to 3, indicating their power law relationship with the fractal pore surface. The values of Dₛ₁ and Dₛ₂ are 2.64–2.98 (2.90 in average) and 2.80–2.98 (2.88 in average), respectively.

Fractal dimensions by sponge model. The fractal curves are divided into two stages based on the classic geometry model (sponge model) (Fig. 4), and thus two fractal dimensions (Dₛ₃, low-pressure and Dₛ₄, high-pressure) are obtained using the mercury intrusion data. Dₛ₃ exhibits a good linear relationship (correlation index R²).

Table 1. Properties of the coal samples having different coal ranks.

| Samples | Cumulative pore volume (cm³/g) | Mean volume (cm³/g) | Mean surface area (m²/g) | Total pore volume (cm³/g) |
|---------|--------------------------------|---------------------|-------------------------|--------------------------|
| S₁      | 0.011 0.009 0.006             | 0.018 0.306 0.026   |                         |                          |
| S₂      | 0.039 0.003 0.024             | 0.030 0.369 0.066   |                         |                          |
| S₃      | 0.015 0.014 0.005             | 0.015 0.158 0.130   |                         |                          |
| S₄      | 0.024 0.010 0.005             | 0.015 0.120 0.062   |                         |                          |
| S₅      | 0.015 0.002 0.075             | 0.082 0.097 0.092   |                         |                          |
| S₆      | 0.019 0.002 0.202             | 0.020 0.234 0.223   |                         |                          |

Table 2. Results of the HPMI and pore distribution for different coal ranks. Note: V₁, V₂, and V₃ are the cumulative pore volumes of <100 nm, 100–10000 nm, and >10000 nm respectively, and Vₜ = V₁ + V₂ + V₃. *no data.
0.82–0.96), whereas $Dg_2$ has a wide range of $R^2$ (0.02–0.91). The values of $Dg_1$ are widely distributed (2.04–3.14, 2.67 in average), indicating significant differences in the discontinuities and roughness of different coal ranks. However, the value of $Dg_2$ are 2.77–3.93 (3.56 in average). Most of the values of $Dg_2$ are close to 3, indicating that the surface is extremely rough and the pore structure is irregular. The values of $Dg_1$ in S1 and S3 are $>3$, and all the values of $Dg_2$ are more than 3, except for sample S1. For the fractal dimensions of 3, numerous explanations have been provided in previous research.

Multifractal analysis. The spectrum curves of $\log \chi(q, \varepsilon)$ versus $\log \varepsilon$ show a linear relationship (correlation index $R^2$, 0.78–1), indicating a multifractal distribution of the pore sizes (Fig. 5). The spectrum curves of the generalized dimensions, $D(q)$, versus $q$ present a sigma-shaped curve and follow a monotone decreasing function of $q$ (Fig. 6a). The characteristic parameters of $D(q)$, dimensions $D_0$, $D_1$, and $D_2$, Hurst exponent $H (2H =D_2+1)$,
width $D_{-10}$-$D_{10}$ of $D(q)$ spectrum, right side width $D_{0}$-$D_{10}$, and left side width $D_{-10}$-$D_{0}$ (Table 3), reflect the inner variability and heterogeneity of the porosity and pore size distribution$^{45,51,57}$. Samples S1 and S6 have the highest and lowest values of $D_{10}$, $D_{2}$, $H$, and $D_{10}$, respectively.

**Propensity to spontaneous combustion.** Fig. 7 displays the results of the CPT measurements performed on the medium-rank and high-rank coals. The CPT ranges from 146.1 to 182.2 °C. Samples S7 (anthracite B) and S1 (bituminous D) have the highest CPT (182.2 °C) and the lowest CPT (146.1 °C), respectively. The CPT increases with increasing coal rank.

**Discussion**

**Effect of evolution of coal petrology on spontaneous combustion.** Relationship between $Rr$ and CPT and pore structure. Coal rank has a significant influence on the propensity of coal to spontaneous combustion (Fig. 8a). A good linear relationship ($R^{2}=0.74$) is exhibited between the coal rank and the CPT. The CPT increases with increasing coal rank, which is in agreement with previous studies$^{58-61}$. However, sample S6 exhibits...
a deviation compared to the other samples. If this sample data are removed, a better linear ($R^2 = 0.89$) is obtained, as shown in Fig. 8a. For the high-rank sample $S_6$, the low CPT may be attributed to its different chemical (low fixed carbon) and physical (low total pore volume) structure, which is in agreement with previous studies\textsuperscript{11,12}. Coal rank is an important index of coalification, influencing the structures of coal pores and fractures. When the vitrinite random reflectance ranges from 0.58 to 2.13\% (Fig. 8b), the mean volume increases with the coal rank, but the mean surface area decreases. When the vitrinite random reflectance ranges from 2.13 to 3.43\% (Fig. 8c), the mean volume decreases with coal rank, but the mean surface area increases with coal rank. When the coalification ranges from 0.5 to 2.1\%, the aromatic structures including non-protonated aromatic carbons (fa\textsuperscript{'}, nuclear magneton resonance (NMR) aromaticity (fa\textsuperscript{-})), and aromatic carbon ratio (fa) increase linearly, whereas the aliphatic structures decreases linearly\textsuperscript{62}. Because the volume is mainly affected by the aliphatic parts of the chemical structure, it may be the cause of the displayed mean volume and surface area trends\textsuperscript{63,64}.

Relationship between coal composition and CPT. There exists a non-linear relationship between the ash content and the CPT, which shows an inverted ‘U-shape’ (Fig. 9a). The CPT is a weakly correlated to the total sulfur content (Fig. 9b). The coal components (volatile matter, oxygen contents, and fixed carbon contents) display good relationships with the CPT (Fig. 9c–e), which is in agreement with Zonguldak coals\textsuperscript{65}. The CPT decreases with increasing volatile matter, indicating that low volatile matter is prone to spontaneous combustion. It may be that low volatile matter content can increase the difficulty of ignition and result in an unstable combustion flame\textsuperscript{66,67}. The relationship between the oxygen content and the CPT also shows the same trend as the volatile matter, indicating that coals with high oxygen content have a high tendency to chemically bind moisture, thereby rendering the surface, highly susceptible to autogenous heating\textsuperscript{68}. The CPT increases linearly with the fixed carbon content, indicating that less fixed carbon content is prone to spontaneous combustion. This is because a small amount of fixed carbon in coal requires a low activation energy to initiate combustion\textsuperscript{69}.

Relationship between pore structure and CPT. Distribution of pore structure and CPT. It is necessary to discuss the relationship between the pore size and the CPT. Fig. 10a shows a weak negative linear correlation between the cumulative pore volume $V_1$ and the CPT, which shows an inverted “U-shape”. Cumulative pore volume $V_2$ shows a “U-shape” (Fig. 10b). The relationship between cumulative pore volume $V_3$ and the CPT exhibit a linear positive correlation (Fig. 10c). Moreover, the total pore volume also has a good linear positive correlation with the CPT ($R^2$ up to 0.71), indicating that pore sizes of more than 10000 nm ($V_3$) play a main role in coal spontaneous combustion (Fig. 10d). Specifically, the pore structure is a dominant factor causing the coal spontaneous combustion, particularly in pore sizes more than 10000 nm.

Relationship between coal rank, pore volume, and multifractal parameters. The entropy dimension ($D_0$) reveals the concentration degree of the porosity distribution\textsuperscript{66}. The values of $D_0$ are less than or equal to $D_0$. When $D_0$ is close to $D_0$, the porosity is evenly distributed. Otherwise, most particles are concentrated in a small area and appear as a high peak on the graph\textsuperscript{70}. Among of all sample S$_i$ has the highest homogeneous pore size distribution. $D_0$ decreases with increasing coal rank (Fig. 11a), indicating an increase in the heterogeneity. However, the fitting results do not a high correlation.
This may be owing to joint action factors such as maceral content, ash content, volatile matter, and tectonic deformations. The relationship between cumulative pore volume \( V_1 \) and \( D_1 \) is not clear, indicating that \( V_1 \) (adsorption-pores) may have little influence on the entropy dimension \( D_1 \) (Fig. 11b). The \( D_1 \) increases with increasing cumulative pore volume \( V_2 \) (Fig. 11c) and decreases with increasing cumulative pore volume \( V_3 \) (Fig. 11d), indicating that seepage-pores have an important influence on the entropy dimension \( D_1 \).

The Hurst exponent \( (H) \) is used to quantify the degree of correlation on the logarithmic scale. If \( H > 0.5 \), the increments are correlated. The Hurst exponent of all the samples exceeds more than 0.5 (H, 0.57–0.97), indicating the increments are correlated (Table 3). The Hurst exponents of samples S1 and S3 are 0.97 and 0.90, respectively, which two data are close to the 1, reflecting the presence of strong persistence or positive autocorrelations. The Hurst exponent has the same characteristics as entropy dimension (Fig. 12).

The width of \( D(q) \) reflects the heterogeneity in the porosity distribution. Sample S7 has the highest \( D_{-10} \)–\( D_{10} \) (the widest spectrum), indicating the highest heterogeneity over the entire pore size range among all the coal samples. In contrast, sample S1 has the lowest \( D_{-10} \)–\( D_{10} \) (the narrowest spectrum), reflecting the lowest heterogeneity in the porosity distribution over the entire pore size range. Samples S3 and S4 have wider right side \( D(q) \) spectra than the left side \( D(q) \) spectra, indicating high dominance of the high porosity concentrations. However, samples S2, S5, and S6 have wider left side \( D(q) \) spectra than right side \( D(q) \) spectra, indicating a small porosity concentration. The widths of the \( D(q) \) \( (D_{-10} \)–\( D_{10} \), \( D_{-50} \)–\( D_{10} \), and \( D_{-10} \)–\( D_{10} \)) spectra increase with increasing vitrinite random reflectance \( (R_r, \%) \) (Fig. 13a). The relationship between cumulative pore volume \( V_1 \) and width of the \( D(q) \) spectra is not clear, indicating that \( V_1 \) (adsorption-pores) may have little influence on the width of the \( D(q) \) spectra (Fig. 13b). The width of the \( D(q) \) spectra logarithmically decreases with increasing cumulative pore volume \( V_2 \) (Fig. 13c) and logarithmically increases with increasing cumulative pore volume \( V_3 \) (Fig. 13d). The above indicates that seepage-pores have an important influence on the heterogeneity in the porosity distribution.

Fractal dimensions and CPT. 1) Multiscale fractal dimensions and CPT. The relationships between the fractal dimensions of the Sierpinski model \( (D_s_1 \) and \( D_s_2 \)) and the CPT are shown in Fig. 11. The relationship between \( D_s_1 \) and the CPT can be divided into two distinct stages (Fig. 14a). In the first stage, the CPT first decreases,
and then increases with increasing $D_{11}$ (when $D_{11} > 2.8$). With increasing $D_{22}$, the CPT decreases first (from 2.75 to 2.85), and then increases (Fig. 14b). Fractal dimensions $D_{11}$ of samples $S_1$ and $S_3$ are >3; however, most of the fractal dimensions, $D_{12}$, are >3, except of sample $S_1$. Fractal dimensions $D_{11}$ and $D_{22}$ are >3, which are not suitable to characterize the pore heterogeneity\cite{25,27}. To prevent the interference of abnormal points, the data for fractal dimensions >3 were removed\cite{37}. The relationship between $D_{11}$ and the CPT (without samples $S_1$ and $S_3$)
displays a similar trend as that between $D_s$ and the CPT obtained from the Sierpinski model (Fig. 14c). When $D_{g1}$ ranges from 2 to 2.6, the CPT decreased significantly. When $D_{g1}$ becomes larger than 2.6, the CPT increases with increasing $D_{g1}$. The above results demonstrate that the heterogeneities obtained from the Sierpinski and Sponge

Figure 12. Relationship between the Hurst exponent ($H$) and the (a) vitrinite random reflectance ($R_r, \%$) and (b–d) Cumulative pore volumes ($V_1, V_2,$ and $V_3$).

Figure 13. Width of the D (q) spectra ($D_{-10}^{10}, D_{0}^{10}, D_{-10}^{0},$ and $D_{-10}^{10}$) and the (a) vitrinite random reflectance ($R_r, \%$) and (b–d) cumulative pore volumes ($V_1, V_2,$ and $V_3$).
models do not present linear relationship with the tendency of coal to spontaneous combustion. However, a high heterogeneity (fractal dimensions >2.8) is associated with a low tendency of spontaneous combustion.

2) Multifractal fractal dimensions and CPT. Fig. 15 displays the correlation between the multifractal fractal dimensions ($D_1$, $D_2$, $H$, $D_{10}$, $D_{-10}$, $D_{10}$, $D_{-10}$, $D_0$, $D_{10}$, $D_{-10}$, $D_0$, $D_{10}$) and the CPT. It can be found that the CPT decreases with increasing parameters $D_1$, $D_2$, $H$, and $D_{10}$, suggesting that a high degree of the distribution of the porosity quantifies the degree of correlation on the log scale. Further, the heterogeneity in the porosity distribution decreases the tendency of coal spontaneous combustion. The correlation between $D_{-10}$, $D_{-10}$, $D_{10}$, $D_{-10}$, $D_0$, $D_{10}$, $D_{-10}$, $D_0$ and the CPT is clear in that the CPT gradually increases with increasing $D_{-10}$, $D_{10}$, $D_{-10}$, $D_0$, $D_{10}$, $D_{-10}$, $D_0$, $D_{10}$. This indicates that the complexity of the local characterization pore structure decreases the spontaneous combustion propensity.

Conclusions
The conventional analysis and CPT measurements were conducted to obtain the properties of coal petrology and spontaneous combustion. Coal rank, volatile matter, oxygen content, and fixed carbon content were found to play important roles in spontaneous combustion.

The pore structure properties obtained from HPMI provided a direct measurement of coal physical properties. The cumulative pore volume of $V_j$ (>10000 nm) and total pore volume have positive correlation with CPT.
Multiscale and multifractal analyses were conducted to evaluate the pore size distribution. From the multi-scale analysis, the relationship between the fractal dimensions ($D_{\alpha1}$, $D_{\alpha2}$, and $D_{\alpha3}$) and the CPT basically displayed a "U-shaped" tendency, with the minimum occurring at 2.6–2.85. Based on the multifractal analysis, a high degree of porosity distribution quantified the degree of correlation on the logarithmic scale. Furthermore, the heterogeneity in the porosity distribution decreased the tendency of coal spontaneous combustion; therefore, a more complex local characterization pore structure lowered the spontaneous combustion propensity.

Received: 17 July 2019; Accepted: 24 January 2020;
Published online: 28 April 2020

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Acknowledgements
This work was supported by National Natural Science Foundation of China (Nos. 41430640 and 41672153) and the Scientific Research Foundation of Key Laboratory of Coalbed Methane Resource & Reservoir Formation Process, Ministry of Education (No. 2017–002).

Author contributions
Zhang Yu: Data processing and paper writing. Zhang Xueqing: Samples preparation. Yang Wen: Samples collection. Xin Haihui: Experimental test. Hu Sherong: Funding and ideas. Song Yu: Method and paper revision.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to H.S. or S.Y.
