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Matrix compression and multifractal characterization for tectonically deformed coals by Hg porosimetry

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ABSTRACT

Concerning the matrix compression and inter-particle volids, the multifractal characteristics [$f(\alpha)$ and D_q] were revealed through LPCO$_2$/N$_2$GA (low temperature CO$_2$/N$_2$ adsorption) and HPMI (high-pressure mercury intrusion) for bituminous TDCs (tectonically deformed coals). The CCs (compression coefficients) increase with the increasing tectonic deformation during brittle deformation stages and decrease for the shear- and ductile deformation coals. The singular index (α_0) transformations demonstrate that the brittle- and shear deformation can promote the PSD (pore size distribution) irregularity. The lower spectral width (α_{q-}-α_{q+}) for the cataclastic- (0.54–0.58, 0.56 in average), mortar- (0.63–0.64, 0.64 in average), and granulitic coals (0.63–0.64, 0.64 in average) indicates the relatively simple multifractal structures of the PSD. While for the shear- and ductile deformed coals, the multifractal structures are complex with high heterogeneity and significant internal differences within PSD. The left-hand side width ($\alpha_{q-} - \alpha_0$) and D_0-D_1 (the difference of information dimension to capacity dimension) increase, indicating that the shear- and ductile TDCs have a more clustered distribution in pore volume than brittle TDCs. There exist good positive linear relationships between D_{ap} (adsorption pores' fractal dimension by Sierpinski model) and left-side width D_{-10}-D_0 ($R^2 = 0.8741$), as well as between D_{sp} (seepage pores' fractal dimension by Sierpinski model) and right-side width D_0-D_{10} ($R^2 = 0.831$), indicating that the variations of multifractal parameters for $q > 0$ are attributed to seepage pores' heterogeneity and these for $q < 0$ are assigned to adsorption-pores' heterogeneity. The D_{-10}-D_0 increases with the increasing deformation intensity, indicating the most complex shapes of the adsorption pores for the ductile TDCs. The D_0-D_{10} firstly decreases for the brittle- and shear TDCs then increases for the ductile TDCs.

1. Introduction

Coal is a porous reservoir where CH$_4$ exists primarily as free phase in macro-pores and fractures, or as adsorbed state on the surface of micro-pores and meso-pores. Pore structure is characterized by pore size, pore shape (PS), pore volume (PV), specific surface area (SSA) and PSD, and all these parameters have significant impact on the accumulation of coalbed methane (CBM) [1,2]. The researches on the structural characteristics such as magnitude, PV, SSA, PS, PSD and connectivity are critical to reveal CBM enrichment mechanism and gas occurrence regularity [3–5].

TDC refers to the structures of coal deformed and destroyed under the effects of tectonic stress [6], which was found widely in many countries that produce coal and was especially prevalent in North China [7]. As the pore structures of tectonically deformed coal exhibit fundamental changes compared with those of primary-structure coal (primary coal), the specific pore structures have a profound impact on the CBM exploration and gas outburst. It is generally accepted that the brittle deformed coals are high-quality CBM development areas while the ductile deformation coals of high incidence for coal and gas outburst [6,8,9]. These differences among coals formed in different deformed environments are attributed to the inner heterogeneity along with the PSD [10], thus, plenty of investigations on the pore structures' heterogeneity in the TDCs have been emerged since last decades [6,10,8,9,11–13]. Ju et al. points out that tectonic deformation has the decisive effect for the nano-pore structures compared with the magma thermal action and it can influence deeply the nanoscale pore structure [12]. By LPN$_2$GA and hysteresis loop analysis, Jiang et al. discovered that gas adsorption are currently in the nanopores about 3.3 nm in size, and the PV-determined fractal dimensions and specific surface area increase with the increasing tectonic deformation intensity [14]. Pan et al. investigated the nanoscale pores of different types of TDCs

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through atomic force microscope (AFM) and proposed that the coal surface exhibited creep flow features, the surface pore morphology of the coal was irregularly developed with the increasing deformation intensity under ductile deformation [15]. Zhang et al. explored the fractal characteristics of nano-pore structure in tectonically deformed coals based on LPN_2GA and FHH model. The results show that ductile deformed coals with higher pore fractal dimensions have higher heterogeneity and more complicated pore structure compared to brittle deformed coals, resulting in higher capillary condensation and prominent adsorption hysteresis loops [16]. Based on the HPMI and Menger fractal model, Yao et al. examined the pore structure of TDCs and demonstrated that the fractal dimension has good applicability to the reveal pore structural characteristics of TDC and deformation characteristics [17]. By small angle X-ray scattering (SAXS) and Frenkel-Halsey-Hill (FHH) fractal model, Pan et al. investigated the heterogeneity of the closed pores in various TDCs and concluded that tectonic movement promotes irregularity and fracturing of the original pores [7]. Song et al. systematically analyzed fractal characteristics of nanopores by combining the LPCO_2/N_2GA, HPMI, and mono-fractal models (FHH and Sierpinski model). The results show that the fractal characteristics of nano-pores can be divided into four groups, i.e., D_1 ($>$ 100 nm), D_2 ($<$ 100 nm), D_3 ($>$ 8 nm), and D_4 ($<$ 8 nm) and strong ductile deformation could have a strong transformational effect on the irregularity of the nanopores, particularly for the adsorption pores [8]. By LPN_2GA and surface fractal model, Li et al. obtained the fractal characteristic of different types of TDCs and demonstrated that the coal body destructive intensities and the heterogeneity of pores can be effectively characterized by fractal dimension [18].

As mentioned above, the fractal works for TDCs are concentrated on mono fractal approaches. Our previous studies have shown that different size intervals have different self-similarity characteristics [2,8,18], which can be reflected through different fractal dimensions, i.e., D_1 ($>$ 100 nm, Sierpinski model), D_2 (3–100 nm, Sierpinski model), D_3 (8–100 nm, FHH model), and D_4 (1.7–8 nm, FHH model), however it is revealed through different fractal models. In addition, the profiles of the pore size distribution of coals especially for the TDCs often show “fluctuations” and “jumps” at different pore size intervals and types of erratic variation or local variation occur in the inner distribution of pore sizes, which cannot be explained by a single-scale (mono-fractal) analysis or a single fractal dimension [8,10]. The single fractal dimension can only describe the pore structural heterogeneity within the specific pore size intervals. These characteristics of different self-similarities for successive pore size scales in TDCs are also widely discovered in many non-homogeneous porous mediums in nature such as sedimentary rocks [19], soils [20,21], and primary coals [22], all of which could be described uniformly as multifractal particles. Peitgen et al. proposed that the complexity of the PSD is caused by the superposition of simultaneously series underlying nonlinear dynamic process for the broad range of the size scale [23]. Thus, the multifractal is an efficient way to reveal the heterogeneous PSD, as well as the inner nonlinear variations, for porous media [24,25]. Li et al. [10] have firstly got deep insights into the variability and heterogeneity of PSDs in cataclastic-, granulitic-, and mylonitic coals using the HPMI and multifractal analysis and the results show that tectonic deformation leads to narrower distribution with higher fluctuation, lower pore connectivity and greater complexity in the distribution of seepage-pores. While, for the absences of the other types of TDCs and the joint effect of the maceral composition, ash content, and moisture content, the multifractal results failed to efficiently and systematically reflect the tectonic deformation effect for the inner structural heterogeneity. On the other hand, the interparticle voids in low pressure regimes were not taken into consideration in Li et al. [10], as well as the multifractal singularity spectra within the multifractal analysis. Thus, it is still not clear what are the multifractal characteristics especially the multifractal singularity spectra for the typical sequential TDCs and how does the pure tectonic deformation affect the multifractal characteristics after eliminating the influences interparticle voids in low pressure and the matrix compression at the high pressure.

Here, interparticle voids and compressibility effects on the HPMI data were both examined by combining the results of LPN_2/CO_2GA with the HPMI for the vitrain TDCs based on the approaches proposed by Li et al. [22]. Then coupled with the multifractal analysis, the multifractal singularity spectrum and generalized fractal dimension spectrum were both comprehensively utilized to investigate the heterogeneity and variability of HPMI PSDs for typical sequential TDCs after compressibility correction and to determine whether the multifractal parameters can be used to compare the variability of PSDs in different bituminous TDCs. Following the recommendations of international unit of pure and applied chemical (IUPAC), pores are classified according to their diameter size as micro-pores ($<$ 2 nm), meso-pores (2–50 nm), and macro-pores ($>$ 50 nm) [26]. Such research is of broad interest in efficient exploration and exploitation of CBM, reservoir evaluation, and the prediction of gas outburst prediction.

2. Experiments and modelling

2.1. Geological setting

Huaibei coalfield is located in the southeast margin of north China plate (Fig. 1a). The Xuzhou-Suxian arcuate double thrust-imbricate fan thrust fault system in Yanshanian [6], which consists of linear compactly closed folds and the thrust-imbricate fan faults, are the main structural features of Huaibei coalfield (Fig. 1b). The strata involved in this nappe structure include Qingbaikou system and Sinian, Cambrian, Ordovician, Carboniferous and Permian, and lower Triassic. The axial lines of the folds and the distribution of faults horizontally exhibit shapes of arcs. Under the influence of regional tectonism, the structure of Huaibei area can be divided into north and south tectonic blocks by the north Suzhou fault. The south tectonic block, located between north Suzhou fault and Banqiao fault, can be divided into east and west tectonic zones by NW directed Xisipo fault. The east tectonic zone lies at the east part of Xisipo thrust fault and it is the front zone of the overlying thrust nappe structure. At the flanks of the east Suzhou syncline, coal seams experience strong compressional deformation, which led to extensive development of tectonically deformed coal. In particular, the coal body exhibited soft and granulates, the texture of coal is severely destroyed under the action of rheomorphism, including the cleats and fractures. The west tectonic zone locates at the west part of Xisipo thrust fault and it belongs to the underlying thrust nappe structure (Fig. 1b). The structural features of this zone are mainly brachy folds with near NS direction and faults with near EW trend. Furthermore, the tectonic deformation in south Suzhou syncline relatively fall off compared with that in east Suzhou syncline [6].

Strata in the Huaibei coalfield consists of upper Proterozoic, Sinian, Cambrian, Ordovician, Carboniferous and Permian, Triassic, Jurassic and Cretaceous, Paleogene, Neogene and Quaternary. Among the strata, Shanxi Formation of the lower Permian and lower Shihezi Formation of the middle Permian are major coal-bearing strata. The main mineable coal seams of the Suzhou mining area are No. 8 coal seam of Xiashihezi Formation and No 10 coal seam of Shanxi Formation as shown in Fig. 1c.

2.2. Samples and experiments

Taking the No. 8 coal from Zhuxianzhang mine in the upper disk of the Xisipo thrust fault and the Qinan mine in the footwall as sampling areas, the samples consist of cataclastic-, mortar-, granulitic-, schistose-, scaly-, wrinkle-, and mylonitic types [2,6,8]. The elemental analysis results of the coal sample were obtained on Vario EL elemental analyzer. Proximate analysis was in accordance with the standard of ASTM Standards D3173-11, D3174-11, and D3175-11. As the coal’s compressibility is comprehensively affected by coal rank, moisture content,