Powder activated coke prepared from coal fast pyrolysis: fractal characteristics and SO₂ adsorption

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Abstract
The rapid and low-cost preparation of powder activated coke (PAC) is very important for the promotion of fluidized dry desulfurization technology of activated coke. In order to explore the effect of rapid pyrolysis process on SO₂ adsorption capacity of PAC, the fractal analysis of PAC prepared under different atmospheres was carried out. The Frenkel–Halsey–Hill (FHH) method was used to determine two fractal dimensions \( D_1 \) and \( D_2 \), under relative pressures of 0–0.5 and 0.5–1, respectively. The results indicate that the fractal dimensions were influenced by the concentrations of activation agents with \( D_1 \) ranging from 2.1838 to 2.8643 and \( D_2 \) ranging from 2.7485 to 2.9257. The effect of steam on the fractal dimension of PAC sample is small, but oxygen has a great promotion effect on the fractal dimension. An n-shaped curve-based relationship between fractal dimensions and coke yields is observed with a peak values of fractal dimensions appearing around 64% yield. The SO₂ adsorption capacity shows a consecutively positive linear correlation with \( D_2 \), while it illustrates distinctly different linear rates with \( D_1 \) in intervals of 2–2.6 and 2.6–3, respectively. Taking advantage of fractal analysis as research method, this paper clarified the influence of activation atmosphere and ablative degree on the SO₂ adsorption capacity of PAC, and the research conclusion provided a basis for the PAC preparation with high SO₂ capacity.

Keywords Fractal characteristics · Powder activated coke · SO₂ adsorption · Activation agent · N₂ gas adsorption

Introduction
SO₂ is one of the major pollutants in coal-fired power plants. At present, limestone–gypsum wet flue gas desulfurization (WFGD) is widely used in most power plants worldwide, especially in China (Zhu et al. 2015). However, this limestone scrubbing desulfurization technology has many disadvantages. The excessive exploitation of Ca-based sorbents has led to serious environmental damage. Meanwhile, the water shortage restricts its application and the difficulty in utilization of desulfurization gypsum causes to the waste of sulfur resources (Ma et al. 2016). For the purpose of saving water resources and recycling sulfur products, the dry flue gas desulfurization, such as the method of SO₂ adsorption using porous adsorbents, has received more attentions (Feng et al. 2020).

Carbonaceous materials, such as activated carbon fiber, activated coke, and carbon nanotubes are clean and recyclable adsorbents for SO₂ removal (Atanes et al. 2012; Gaur et al. 2006; Yan et al. 2013). Among these adsorbents, powder-activated coke (PAC) causes aboard attention of many researchers as an ideal SO₂ adsorbent in practical process, because of low cost, low abrasion loss, and high adsorption speed. In our previous study, we originally proposed a rapid preparation process of PAC by one-step activation method under low oxygen atmosphere and PAC with high specific surface area and well-developed pore structure was prepared (Zhang et al. 2016).

The SO₂ adsorption capacity of PAC is put down to its physicochemical characteristics. Previous research has shown that high surface area, large pore volume, suitable microporosity, and appropriate pore size distribution are the most important requirements for SO₂ adsorption (Raymundo-Piñero et al.
In addition, several researchers suggested that active sites, such as basic oxygen surface groups, CO-derived active sites, or heteroatoms, also play a significant role in SO₂ adsorption (Davini 1990; Sun et al. 2016; Wang et al. 2018). It is worth noting that the active sites also need to be in a specific pore structure to exert effects on SO₂ adsorption. Therefore, it is of great significance to understand the pore structure formation mechanism of porous carbon material and figure out the effect of pore structure on SO₂ adsorption performance for improving the adsorption performance of carbonaceous adsorbent.

Many investigations have shown that the fractal analysis is an effective method to describe the geometric and structural properties of fractal surfaces, pore structures, surface heterogeneity, etc. (Yakout and El-Deen 2016; Zhang et al. 2014). It was discovered that the pores of some carbon materials, such as char and coal, were fractal-like, and the preparation conditions of carbon materials affect the fractal dimension. The fractal dimension is closely related to the burn-off ratio, pyrolysis temperature, and heating rate during coal devolatilization (Chen et al. 2011; Xu et al. 2010). Through the research on the evolution of fractal dimension during CO₂ gasification of lean coal, it is found that when the burn-off ratio is less than 48%, the tri-dimensional properties of micropores are better and the pore structure becomes more complex with increasing burn-off ratio (Wang et al. 2020). Previous study also revealed that the fractal dimension of coal char particles is positively correlated with the burn-off ratio, and the fractal dimension increases by increasing the gasification temperature (Chen et al. 2022). In addition, it is reported that the fractal dimension of activated carbon activated by CO₂ was higher than that activated by steam at the same ablation rate (Liu et al. 2021). However, the fractal study of coke in low oxygen rapid pyrolysis process is scarce at present.

This fractal theory has also been applied in studies on gas adsorption characteristics. For instance, the CH₄ adsorption capacity is positively correlated with the pore fractal characteristics (Wang et al. 2012; Naveen et al. 2018; Yang et al. 2014; Yao et al. 2008). Researches show that higher fractal dimension D₁ correlates to more irregular surfaces that provide more space for CH₄ adsorption. Higher fractal dimension D₂ represents higher heterogeneity of pore structure that reduce CH₄ adsorption capacity (Naveen et al. 2018; Yao et al. 2008). Nevertheless, there are no reports about the relationship between SO₂ adsorption and fractal dimension.

In summary, although the pore fractal characteristics of raw coals, pyrolytic cookes, and activated carbons have been reported in previous literatures, there are few studies on the influence of preparation atmosphere on fractal dimension in low oxygen rapid pyrolysis and the correlation of the fractal dimension with the SO₂ adsorption capacity. Therefore, the present work investigates the effects of the activation agents and coke yield on the fractal dimension in detail. In addition, the impact of the fractal dimension on the SO₂ adsorption capacity is also discussed. This type of investigation could enrich knowledge on the nature of porous solids and the related adsorption processes. The fractal characteristics of PAC during fluidized fast pyrolysis process and its influence of SO₂ adsorption are also provided.

### Experiment

#### Sample preparation

Lean coal was used as a precursor material for PAC preparation. Firstly, the lean coal raw material was dried at 105 °C for 8 h, and then the sample was crushed, ground, and sieved, and finally, the granular product (particle size 60–90 μm) was obtained. PAC was prepared at atmospheric pressure in a drop tube reactor (DTR) system. The experimental system is shown in Fig. 1.

The reactor in this system is composed of 310S stainless steel tubes with an inner diameter of 80 mm and a depth of 2 m. When the reaction gas temperature reaches 850°C, nitrogen (10 L·min⁻¹, STP) is used as primary carrier gas to carry the pulverized coal into DTR at a mass flow rate of 0.5 g·min⁻¹. According to literature (Hayashi et al. 2000), coal particles in DTR were heated to 850 °C at high heating rate (> 10⁵ K·s⁻¹). The secondary carrier gas was selected from the three gas mixtures (nitrogen/steam, nitrogen/oxygen or nitrogen/steam/oxygen) and entered the system at the rate of 10 L·min⁻¹ (STP). As coal particles were continuously fed into the reactor, the volatile components released from the coal particles and the char reacted with volatile and activation gas (oxygen and steam) to form activated coke. The active coke particles generated by the reaction were collected at the bottom of DTR and further analyzed. The prepared PAC was named PAC-OₓSy, where x represents the concentration of oxygen in the activator, and y represents the volume concentration of water vapor in the activator. Oₓ or Sᵧ can be omitted when activation agents contained neither oxygen nor steam. In addition, the PACs prepared using nitrogen atmosphere were named as PAC-N. The specific surface area and pore structure of each sample are shown in Table 1.

#### Yield of PACs

The PAC yield plays an important role in adsorption performance evaluation, which is related to the economy of the process and adsorption capacity. Due to mass loss from the release of volatile substances, the yield could not be determined by direct weighing. Hence, the ash balance method was adopted.
for yield calculation, which defines the mass of ash in row coal and PACs are unchanged during PAC preparation. The yield $Y_{PAC}$ is calculated as follows:

$$Y_{PAC} = \frac{A_{coal}}{A_{PAC}}$$  \hspace{1cm} (1)
Calculation of fractal dimension

In previous studies, the fractal dimension was obtained via various methods, such as mercury intrusion, transmission electron microscopy, small-angle X-ray scattering, and N\textsubscript{2} gas adsorption (Pan et al. 2016; Wang et al. 2014; Yang et al. 2014; You et al. 2015). Among these methods, N\textsubscript{2} gas adsorption analysis has been shown to be an effective method for characterizing fractal dimensions (Hayashi et al. 2002; Wang et al. 2015).

Different approaches, such as fractal BET, fractal Langmuir, the thermodynamic method, and the fractal Frenkel–Halsey–Hill (FHH) method, can be used to derive the fractal dimension based on gas adsorption isotherms (Kanô et al. 2000; Mahnke and Mögel 2003; Vajda and Felinger 2014). The FHH approach has been shown to be the most effective and extensively used method for determining surface irregularity in porous materials (Naveen et al. 2018). Using the FHH method, the fractal dimension can be determined from an analysis of multi-layer adsorption onto a fractal surface according to the following equation:

\[
\ln \frac{V}{V_m} = \text{constant} + A \left[ \ln \left( \frac{P_0}{P} \right) \right]^{\beta} \tag{2}
\]

where \(V\) is the volume of adsorbed gas molecules at equilibrium pressure \(P\); \(V_m\) is the volume of monolayer coverage; \(A\) is the power-law exponent that is dependent on fractal dimension \(D\) and the mechanism of adsorption; and \(P_0\) is the saturation pressure of the gas. The findings shown above were obtained using a low-temperature nitrogen adsorption test. N\textsubscript{2} adsorption isotherms of the PACs at 77 K (−196 °C) were obtained using an automated gas sorption analyzer (Autosorb-iQ). The PAC samples were degassed for 12 h under vacuum at 200 °C before the gas adsorption tests. Plotting the N\textsubscript{2} adsorption isotherm data in the form \(\ln \ln (P_0/P)\) yields the \(A\) value. The fractal dimension may then be calculated using the graph’s slope (\(A\)). There are two formulas for calculating the fractal slope: \(D = 3 + 3A\) and \(D = 3 + A\). The former is used in a van der Waals force regime, whereas the latter is used in a capillary condensation regime (Pfeifer et al. 1989; Zhang et al. 2014). According to prior research, both formulas are often utilized; however, the fractal dimensions determined with the former are generally smaller than 2. This value does not correspond to the definition of a fractal dimension, but the fractal dimensions estimated with the latter range from 2 to 3. In this study, the fractal dimension is estimated using \(D = 3 + A\) (Liu et al. 2015).

SO\textsubscript{2} adsorption capacity of samples

In a fixed-bed testing equipment (shown as Fig. 2), the PACs’ adsorption capability was examined. The experiment setup is composed of simulated flue gas system, fixed-bed reactor, and a gas analyzer. The simulated flue gas obtained via controlled mixing of 0.14vol.% SO\textsubscript{2}, 8 vol.% H\textsubscript{2}O, 6 vol.% O\textsubscript{2}, and 85.86 vol.% N\textsubscript{2} was continuously fed into reactor at a rate of 400 mL min\(^{-1}\). The steam is fed through the saturated steam carried by nitrogen. The thermostatic water bath temperature is kept at 55 °C, and the pipe which the steam passes through is kept at 120 °C by the heat band. The carbon bed containing 1 g PAC was used to adsorb SO\textsubscript{2} in a fixed-bed reactor with an inner diameter of 15 mm and a length of 500 mm at 75 °C. An online Fourier transform infrared gas analyzer was used to continually monitor the SO\textsubscript{2} concentration (GASMET-DX4000). Using the following equation, the SO\textsubscript{2} adsorption capacity \(Q_{ad}\) was estimated by integrating the SO\textsubscript{2} conversion versus time curves:

\[
Q_{ad} = \frac{Q_m M}{22.4 \times m} \int \left( C_{in} - C_{out} \right) dt \tag{3}
\]

Fig. 2. Experimental system for SO\textsubscript{2} adsorption by PAC
where \( M_{\text{ad}} \) is the adsorption capacity per gram, \( Q_g \) is the volumetric flow rate of the simulated flue gas, \( C_{\text{in}} \) and \( C_{\text{out}} \) represent the initial and out concentrations of \( \text{SO}_2 \) in the simulated flue gas, respectively, \( M \) is the molar mass of the adsorbate, \( m \) is mass of the PAC in the experiment, and \( t \) is the absorption time. Unfortunately, \( \text{SO}_2 \) adsorption is a sluggish process, with saturation adsorption taking hundreds of hours. As a result, the adsorption time was lowered to 2 h for practical reasons (Jastrząb 2012).

**Results and discussion**

**Fractal characterization of PACs**

Fractal dimensions are estimated via the FHH model to linearly fit the correlation between the adsorbed volume \( \ln V \) and \( \ln[\ln(P/P_0)] \). According to the calculated slopes, there are different rules in the \( P/P_0 \) ranges of 0–0.5 (pore size < 10 nm) and 0.5–1 (pore size ≥ 10 nm) due to the different sorption mechanisms in pores with different sizes (Cai et al. 2013; Wang et al. 2012; Naveen et al. 2018; Yao et al. 2008). As shown in Fig. 3, no linear relationship was observed in the \( \ln V \) versus \( \ln[\ln(P/P_0)] \) plot of PAC-N in the \( P/P_0 \) range of 0–0.5 and the fractal dimension is unrealistically low (\( D < 2 \)) in the \( P/P_0 \) range of 0.5–1. This may be due to the amorphous carbon consumption, surface microcrystal gra phitization, and pore collapse of carbon materials caused by high temperature, so that they do not present fractal characteristics. The plots of PAC-Ox exhibit two distinct linear ranges and both have high degree of linearity (\( R^2 > 0.98 \)), suggesting that the fractal characteristics are diverse in these two ranges. Hence, in the regions of \( P/P_0 < 0.5 \) and \( P/P_0 \geq 0.5 \), the fractal dimensions were estimated and defined as \( D_1 \) and \( D_2 \), respectively. According to previous studies (Bu et al. 2015; Zhu et al. 2016), \( D_1 \) reflects the pores surface roughness of a porous carbon structure, and hence, it can be used to represent the pores surface irregularity. \( D_2 \) reflects...
the volumetric roughness of a porous carbon structure and it can be used to represent the pore structure complexity. The other sample’s FHH plots, such as PAC-OxSy and PAC-Sy, are similar to those of PAC-Ox, which are not presented here.

The slopes ($A_1$ and $A_2$) and fractal dimension values ($D_1$ and $D_2$) of the PACs obtained by the FHH model are presented in Table 2. $D_1$ varies from 2.1838 to 2.4673 under an oxygen-free atmosphere, which suggests that these PACs have smooth pore surface and few micropore structures. In the meantime, $D_2$ varies from 2.7455 to 2.8074 under an oxygen-free atmosphere, indicating that the PACs have irregular particle surface and several of mesopore and macropores. Obviously, the $D_1$ and $D_2$ values of the PAC prepared under in oxygen-bearing atmosphere are higher than those of other PACs prepared in an oxygen-free atmosphere. This shows that oxygen acts is an vital activator for the development of pore structures and rough surfaces during PAC preparation (Yakout and El-Deen 2016). The PAC prepared under a 15% steam and 7% oxygen concentration has the highest $D_1$ and $D_2$ values. By comparison with Tables 1 and 2, it can be found that although PAC prepared under in oxygen-bearing atmosphere has more abundant microporous structure and higher fractal dimension than in an oxygen-free atmosphere at the same time, the variation rule of fractal dimension is not consistent with direct parameters such as $V_{tot}$, $V_{micro}$, $S_{tot}$, $S_{micro}$, and $r_p$.

### Relation between fractal dimensions and activation agent concentration

The relationship between the fractal dimension and activation agent concentration is shown in Fig. 4. The $D_1$ value is always less than the $D_2$ value. As shown in Fig. 4a, $D_1$ and $D_2$ increase as the O$_2$ concentration increases from 2 to 7% and then slightly decreases as the O$_2$ concentration increases to 8%. $D_1$ exhibits similar tendencies with regard to $D_2$.

This accounts for the higher reactivity of O$_2$ with C and combustible gases in the volatile. The high reactivity contributes to rapid release of volatiles and formation of the pore structure at the initial stage of reaction; thus, it increases the pore surface roughness and pore complexity of PACs. However, higher O$_2$ concentration causes excessive ablation of carbon surface and collapse of pore structure, resulting in the decrease of fractal dimension. Figure 4b shows the relation between the H$_2$O concentration and fractal dimension of the PACs prepared with H$_2$O activation alone. The results show that the H$_2$O concentration does not have much influence on $D_2$. However, the $D_1$ value changes significantly as the H$_2$O concentration increases and the maximum $D_1$ value is obtained at a H$_2$O concentration of 25%. With further increase of H$_2$O concentration, $D_1$ value decreased significantly. It indicates that the effect of H$_2$O on carbonaceous materials is mainly reflected in the ablation of carbon matrix surface and the expansion and improvement of existing pore structure. Although steam activation results in higher $D_1$ values, the $D_1$ values are still much lower than that of the PACs prepared in the oxygen-bearing atmosphere. The reason is that the rate of reaction between steam and coal is much slower than that between oxygen and coal. Moreover, when H$_2$O exists alone, the temperature of carbon particles declines and the release of volatiles is hindered due to endothermic reaction between C and H$_2$O. In this case, the creation of pore structure in the course of the initial pyrolysis stage is negatively affected, resulting in a lower fractal dimension. Figure 4c indicates the association between the fractal dimension and H$_2$O concentration for PACs prepared under a mixed O$_2$ and H$_2$O atmosphere with O$_2$ concentration varies from 2 to 7%.

### Table 2 Fractal dimensions and yields of PACs

| Sample | $P/P_0 = 0–0.5$ | $P/P_0 = 0.5–1$ | Yield (%) |
|--------|----------------|-----------------|-----------|
|        | $A_1$ | $D_1$ | $R^2$ | $A_2$ | $D_2$ | $R^2$ |       |
| PAC-N  | —     | —     | —     | —     | —     | —     | 84.90 |
| PAC-S15| −0.8162 | 2.1838 | 0.9981 | −0.2515 | 2.7485 | 0.9920 | 83.12 |
| PAC-S25| −0.5327 | 2.4673 | 0.9978 | −0.2361 | 2.7639 | 0.9908 | 79.58 |
| PAC-S35| −0.6077 | 2.3923 | 0.9903 | −0.1926 | 2.8074 | 0.9591 | 78.35 |
| PAC-S45| −0.7724 | 2.2276 | 0.9959 | −0.2545 | 2.7455 | 0.9875 | 75.31 |
| PAC-O2 | −0.3414 | 2.6586 | 0.9891 | −0.1820 | 2.8180 | 0.9788 | 73.27 |
| PAC-O4 | −0.2050 | 2.7950 | 0.9970 | −0.1026 | 2.8974 | 0.9926 | 71.46 |
| PAC-O6 | −0.2042 | 2.7958 | 0.9911 | −0.1016 | 2.8984 | 0.9808 | 70.56 |
| PAC-O7 | −0.1936 | 2.8064 | 0.9940 | −0.0914 | 2.9086 | 0.9923 | 68.88 |
| PAC-O8 | −0.2136 | 2.7864 | 0.9989 | −0.0923 | 2.9077 | 0.9865 | 64.44 |
| PAC-O7S15| −0.1357 | 2.8643 | 0.9658 | −0.0743 | 2.9257 | 0.9868 | 58.18 |
| PAC-O7S25| −0.1829 | 2.8171 | 0.9874 | −0.1238 | 2.8762 | 0.9957 | 54.92 |
| PAC-O7S35| −0.2295 | 2.7705 | 0.9816 | −0.1382 | 2.8618 | 0.9926 | 62.49 |
| PAC-O7S45| −0.3032 | 2.6968 | 0.9946 | −0.1603 | 2.8397 | 0.9924 | 55.12 |
concentration fixed at 7%. $D_1$ increases from 2.81 to 2.86 and $D_2$ increases from 2.91 to 2.93 with increasing $H_2O$ concentration from 0 to 15% and then decreases at higher steam concentrations. It indicates that, under a mixed $O_2$ and $H_2O$ atmosphere, the volatiles release rapidly and the original closed pores are opened at the initial pyrolysis stage. After the devolatilization stage, $O_2$ and $H_2O$ react with carbon surface to form new pore structures. Moderate steam can compete with $O_2$ for the reaction site. This avoids excessive ablation of carbon materials by $O_2$ to a certain extent and maintains the complexity of internal surface and irregularity of pore structures. However, further increase of $H_2O$ concentration will lead to pore size expanding and pore structure collapse, which will destroy the original micropore structure and reduce the fractal dimension.

**Relationship between fractal dimension and yield**

The relationship between the fractal dimension of PAC and coke yield is shown in Fig. 5. It can be seen that their relationship curve is n-shaped. $D_1$ and $D_2$ reached the maximum when the yield of PAC was about 64%. This illustrates that the yield of PAC has a great influence on the fractal dimension. The relationship between fractal dimension and the yield can be expressed by the following formula:

$$D_1 = -1.26 \times 10^{-3} Y_{PAC}^2 + 0.16 Y_{PAC} - 2.04$$  \hspace{1cm} (4)

$$D_2 = -4.25 \times 10^{-4} Y_{PAC}^2 + 0.054 Y_{PAC} + 1.17$$  \hspace{1cm} (5)
When the yield is high, carbon ablation is not the primary factor affecting the fractal dimension. The release of volatile matter may lead to generation of smoother pore surface and closure of some open pores inside the particles. This results in a lower fractal dimension. However, when the yield decreases, the ablative degree of carbon matrix increases with the increase of amorphous carbon and carbon crystal consumption and a large number of micropores and mesopores will be produced. As presented in Tables 1 and 2, the PAC samples around the yield corresponding to the highest fractal dimension have larger micropore volume and micropore specific surface area, which means that the surface irregularity and pore complexity are higher, so the fractal dimension is also larger. As \( Y_{PAC} \) further declines, the fractal dimension decreases with the decrease of yield due to the excessive consumption of amorphous carbon and carbon crystalline carbon. In other words, moderate ablation can maximize the surface complexity and pore irregularity of carbon materials.

**Relation between fractal dimensions and SO\(_2\) adsorption characteristics**

The SO\(_2\) adsorption properties of PACs were estimated using an adsorption breakthrough curve over 120 min. As observed in Fig. 6, the SO\(_2\) adsorption breakthrough curves of the PACs varied with the \( O_2 \) and \( H_2O \) concentrations in the activation agent. The value of \( C/C_0 \) rapidly increased to 0.8 after 20 min, and saturation (\( C/C_0 =1 \)) occurred after 120 min for PAC-N prepared under a \( N_2 \) atmosphere, corresponding to the lowest adsorption capacity of 10.27 mg·g\(^{-1}\). Although \( H_2O \) activation could improve the SO\(_2\) adsorption capacity of PAC, saturation adsorption still occurred within 120 min. This results in a limited increase in SO\(_2\) adsorption from 13.85 to 17.12 mg·g\(^{-1}\) with increasing adsorption capacities of four PACs prepared via \( H_2O \) activation alone, following a decreasing trend of PAC-S35>PAC-S25>PAC-S45>PAC-S15. However, PAC prepared under an oxygen-containing atmosphere showed a better gas adsorption performance than PAC-N and PAC-Sy. According to Fig. 6b, the SO\(_2\) sorption was significantly improved and the \( C/C_0 \) value decreased from 0.9 to 0.77 as the \( O_2 \) concentration increased from 2 to 7% but then decreased when PACs were prepared using \( O_2 \) activation alone. The SO\(_2\) adsorption capacity of PAC-O7 activated using 7% \( O_2 \) is 39.14 mg·g\(^{-1}\), which is approximately 3.8 times than that of PAC-N. Figure 6c shows that activation with a mixture of oxygen and an appropriate concentration of steam can further improve the SO\(_2\) adsorption capacity. With an increasing \( H_2O \) concentration from 0% to 15%, the value of \( C/C_0 \) decreases from 0.77 to 0.67 and then increases. Correspondingly, the SO\(_2\) adsorption capacity of PAC-O7S15 achieves the maximum, 45.85 mg·g\(^{-1}\), which is approximately 1.2 times and 4.6 times than those of PAC-O7 and PAC-N, respectively. This demonstrates that PACs prepared under an atmosphere of oxygen mixed with steam are ideal for the SO\(_2\) removal.

Figure 7 is the curves of fractal dimension \( D_1 \) and \( D_2 \) with SO\(_2\) adsorption. It can be seen that the curves in Fig. 7a and
b are significantly different, indicating that $D_1$ and $D_2$ have different effects on SO$_2$ adsorption. It can be seen in Fig. 7a that there are two lines, whose fractal dimension ranges are 2–2.6 and 2.6–3. Both lines showed a good linear relationship between fractal dimension ($D_1$) and SO$_2$ adsorption capacity. At the same time, it can be seen that the slopes of the two lines were significantly different, indicating that the relationship between fractal dimension and SO$_2$ adsorption capacity was also different in these two fractal dimensions. The PAC with a higher $D_1$ value has a more complex microporous surface, which provides more sites for SO$_2$ adsorption. As mentioned above, the $D_1$ value of PAC prepared under anaerobic conditions is lower than that of PAC prepared under an oxygen atmosphere, and its SO$_2$ adsorption capacity increases sharply with the increase of fractal dimension. The SO$_2$ adsorption capacity of PAC prepared in an oxygen-containing atmosphere increases with the increase of fractal dimension. This indicates that the addition of O$_2$ promotes the heterogeneity of pore surface and produces more functional groups that cannot be expressed in fractal dimension compared with H$_2$O activation. These functional groups can provide more active centers for SO$_2$ adsorption, thus promoting the improvement of SO$_2$ adsorption performance (Fu et al. 2020). As shown in Fig. 7b, the SO$_2$ adsorption capacity of PAC increases with the increase of $D_2$ value. The high value of $D_2$ may be due to the existence of more micropores and mesopores in PAC, and the heterogeneity of pore distribution also affects the value of $D_2$. The types and distribution of pores provide more space for SO$_2$ adsorption and more storage space for product sulfuric acid. In summary, under the premise of the same physical structure and chemical properties of carbonaceous materials, fractal dimensions can fully reflect the influence of PAC performance on SO$_2$ adsorption (Li et al. 2016; Mahamud et al. 2003).

**Conclusions**

The FHH method was applied to investigate the fractal characteristics related to the SO$_2$ adsorption properties of PACs. The effects of the activation agent and yield on the fractal dimensions of PACs were studied. Furthermore, the influence of the fractal dimension on the SO$_2$ adsorption capacities of PACs was analyzed. The main findings are as follows:

The fractal dimensions were influenced by the activation agent and concentration. Oxygen, as an activated gas, can produce higher fractal dimension than steam. When the activated gas contains H$_2$O, the $D_1$ value of PAC prepared under an oxygen-free atmosphere is much less than that of PAC prepared under an oxygen-containing atmosphere. The maximum $D_1$ and $D_2$ values were observed when PAC was prepared under 7% O$_2$ and 15% H$_2$O.

The PAC yield had a significant effect on the fractal dimensions. The relationship between the fractal dimensions ($D_1$ and $D_2$) and yield can be represented by an n-shaped curve, with a maximum value at approximately 64% yield.

The SO$_2$ adsorption characteristics differ for the PACs. PACs prepared under an atmosphere of oxygen mixed with steam are favorable for the removal of SO$_2$. The SO$_2$ adsorption capacity of PAC-O7S15 is the highest, at 45.85 mg·g$^{-1}$. The fractal dimensions can comprehensively reflect the pore structure properties and the influence of the properties of coal on SO$_2$ adsorption.

However, the influence of reaction temperature, pyrolysis time, and other preparation factors on fractal dimension was not studied in this paper, so the direct relationship equation between reaction conditions and adsorption SO$_2$ capacity could not be established. The relationship between fractal dimension and pore structure parameters also needs to be studied in the future.

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