Research Article

Kinetics of SO₂ Adsorption on Powder Activated Carbon in a Drop Tube Furnace

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1. Introduction

Emission of sulfur dioxide (SO₂) has resulted in worldwide concerns in recent decades [1–3]. Adsorptive flue gas desulfurization (FGD) by activated carbon (AC) has been utilized in various industrial processes due to the advantage in recycling SO₂ as sulfuric acid or sulfur and combined removal of other hazardous gases [1–7]. Conventional adsorptive FGD uses pelletized AC with 5–9 mm diameter as adsorbent in the moving bed reactor. Efficient removal of SO₂ is achievable with this method. However, high construction investment and operating consumption have always been a concern in some commercialization. The costs are mainly derived from the consumption of AC, which further results from the low utilization of inner part of pelletized AC and abrasion [8–10]. The powdered AC with diameter less than 100 μm, that was expected to have higher utilization ratio and lower production cost compared with the pelletized AC, is selected as the adsorbent in a novel method proposed by Ma [8, 11, 12]. The circulating fluidized bed (CFB) reactor is designed in the new method.

As for SO₂ adsorption fundamentals over AC, the following processes have been widely accepted with researchers [7]. The SO₂ in flue gas is first adsorbed on the surface of AC and then catalyzed to sulfuric acid (H₂SO₄) and H₂SO₄ is stored in pores of AC. The relevant reactions involved are as follows [7]:

\[
\begin{align*}
\text{SO}_2 \text{(gas)} + X_V & \rightarrow \text{SO}_2 \text{(ad)} \quad (1) \\
\text{O}_2 \text{(gas)} + X_V & \rightarrow \text{O}_2 \text{(ad)} \quad (2) \\
\text{H}_2\text{O} \text{(gas)} + X_V & \rightarrow \text{H}_2\text{O} \text{(ad)} \quad (3) \\
2\text{SO}_2 \text{(ad)} + \text{O}_2 \text{(ad)} & \rightarrow 2\text{SO}_3 \text{(ad)} \quad (4) \\
\text{SO}_3 \text{(ad)} + \text{H}_2\text{O} \text{(ad)} & \rightarrow \text{H}_2\text{SO}_4 \text{(ad)} \quad (5)
\end{align*}
\]

where (gas) is for gas phase, X_V denotes the vacant sites, and (ad) represents the adsorbed species.

According to the adsorption mechanism above, the powdered AC would certainly show more rapid SO₂ adsorption rate compared with the pelletized AC due to larger surface area exposed to the gas and shorter diffusion distance
In order to simplify the value, the AC-SO2 (AC/S) molar ratio is proposed in this paper. With the assumption that the molar mass of activated carbon is 12 g/mol, AC/S molar ratio is defined as the molar ratio of AC to SO2.

The relative amount of SO2 and AC in the gas flow is an important value that would affect the adsorption dynamics. In order to simplify the value, the AC-SO2 (AC/S) molar ratio is proposed in this paper. With the assumption that the molar mass of activated carbon is 12 g/mol, AC/S molar ratio is defined as the molar ratio of AC to SO2.

Aimed at studying the adsorption dynamics in CFB, continuous supply of simulated flue gas and powdered AC in the experiment is essential. A drop tube reactor which can supply stable AC/S molar ratio with easy access as bench scale study is designed to simulate the adsorption process in CFB reactor.

In the paper, the SO2 adsorption kinetics on powdered AC is performed in a laboratory-scale drop tube furnace. The reaction conditions affecting the adsorption of SO2, such as AC/S molar ratio, temperature, the concentration of SO2, O2, and H2O, and AC circulation rate, are studied. The SO2 adsorption kinetics model is also proposed.

2. Experiments and Methods

2.1. Activated Carbon. A granular AC, which was made from coal by Shanghai Activated Carbon Co., Ltd., was used as raw material. The granular ACs were ground and screened and then 0.075 mm powdered ACs were selected as the research object. The N2 adsorption isotherms of AC were measured at 77 K by a Micromeritics ASAP2020 instrument. The Brunauer-Emmett-Teller (BET) equation and t-plot method were used to calculate the specific surface area (S(BET)) and the micro pore specific surface area (S(mic)) of AC, respectively. The t-plot method and the Barrett-Joyner-Halenda (BJH) method were used to calculate the micropore volume (V(mic)) and mesopore volume (V(mes)), respectively. The Horvath-Kawazoe (HK) method was used to calculate the micropore size (L(mic)). The HK method and BJH method were used to calculate the size distribution of micropore and mesopore, respectively.

The Fourier transformed infrared spectroscopy (FT-IR) spectra of the powdered AC was measured by Vertex-70 from Brook Company in Germany. The spectrum was recorded from 4000 to 400 cm−1 at a resolution of 4 cm−1.

2.2. SO2 Adsorption. The SO2 adsorption kinetics on the powdered AC was performed in a laboratory-scale drop tube furnace, and the system diagram of the drop tube furnace is shown in Figure 1. The stainless steel reactor of the drop tube furnace is 2 meters in length and 40 mm in diameter. The reaction temperature is controlled by an electric heating device. There are five gas sampling holes, which were evenly arranged along the reactor, to measure SO2 concentration. The MFEV-IVO microfeeder continuously and uniformly delivers the powdered AC into the reactor.

SO2, O2, H2O, and N2 constitute the simulated flue gas and the concentration of SO2, O2, and N2 is controlled by mass flowmeters (Sevenstar CS200). The peristaltic pump transports deionized water to the evaporator to generate water vapor before entering the reactor. The flow rate of the simulated flue gas is 20 L/min. The SO2 concentration is between 0.015% and 0.1%, the O2 concentration is between 0% and 6%, the H2O concentration is between 0% and 8%, and the rest is N2. The reaction temperature is between 65 °C and 95 °C.

The FT-IR gas analyzer (Gasmet Dx4000) was used to measure the SO2 concentration in flue gas. The SO2 removal rate by the powdered AC was determined by the following equation:

$$\eta = \frac{C_{SO2-in} - C_{SO2-out}}{C_{SO2-in}} \times 100\%,$$

where η is desulfurization efficiency, $C_{SO2-in}$ is the SO2 concentration at the reactor inlet, and $C_{SO2-out}$ is the SO2 concentration at the sampling port.

The adsorption amount of SO2 on the powdered AC was determined by the following equation:

$$q = 28.6 \frac{C_{SO2-in} V \eta}{m_{AC}},$$

where $q$ is the adsorption amount of SO2 on the powdered AC. mg/g, V is the flue gas flow rate, L/min, and $m_{AC}$ is the feeding rate of the powdered AC, g/min.

3. Results and Discussions

3.1. Characterization of the Powdered AC. The N2 adsorption isotherms of the granular AC and powdered AC are shown in Figure 2, the shape of which is type I according to IUPAC, indicating that the powdered AC mainly contains micropores [13].

Table 1 shows the pore structure parameters of the granular AC and powdered AC. Figure 3 shows the pore-size distribution of the granular AC and powdered AC. The value of $S_{mic}$ of the powdered AC is 541 m2/g, which is larger than that of granular AC. The value of $V_{mic}$ of the powdered AC is 0.699 nm, which is larger than the molecular dynamics diameter of SO2, O2, and H2O, meaning that SO2, O2, and H2O can diffuse into the micropores of the powdered AC. [8]

Because the particle mass transfer and pore diffusional resistances of the granular AC are larger than those of the powdered AC, N2 molecules cannot diffuse into some micropores inside the granular AC; therefore, the values of $S_{BET}$, $S_{mic}$ and $V_{mic}$ of the granular AC are lower than that of the powdered AC.

The FT-IR spectrum of the powdered AC is shown in Figure 4. The sample had adsorption bands at around 1560, 1414, and 1107 cm−1. The one at 1560 cm−1 could be associated with quinone and carbonyl groups. The 1414 cm−1 can be attributed either to carboxyl groups or to phenolic hydroxy groups. The adsorption band at 1107 cm−1 is related to C-O stretching in ethers, lactones, and phenols [8].
3.2. Influence of AC/S Molar Ratio on SO\textsubscript{2} Adsorption.

The influence of AC/S molar ratio on the adsorption of SO\textsubscript{2} by the powdered AC is shown in Figure 5. The flow rate of the simulated flue gas is 20 L/min, and therefore the gas residence time in the reactor is about 6 seconds. In the first 1.2 seconds, the powdered AC quickly adsorbs SO\textsubscript{2}, and the amount of SO\textsubscript{2} adsorbed rapidly increases. And then the SO\textsubscript{2} adsorption rate by the powdered AC decreases and the amount of SO\textsubscript{2} adsorbed slowly increases. As shown in the reaction equations (1)–(5), the SO\textsubscript{2} in flue gas is first adsorbed on the surface of AC and then catalyzed to H\textsubscript{2}SO\textsubscript{4} and H\textsubscript{2}SO\textsubscript{4} is stored in pores of AC. The concentration difference between SO\textsubscript{2} in flue gas and SO\textsubscript{2} on the surface of the powdered AC is the driving force for the powdered AC to adsorb SO\textsubscript{2}. As the adsorption progresses, the active sites on the surface of the powdered AC are occupied by SO\textsubscript{2}, and the number of the vacant active sites decreases. The concentration of SO\textsubscript{2} on the surface of the powdered AC is increased while the concentration of SO\textsubscript{2} in flue gas is decreased. The concentration difference between SO\textsubscript{2} in flue gas and SO\textsubscript{2} on the surface of the powdered AC is therefore decreased and then the driving force for the powdered AC to adsorb SO\textsubscript{2} is also decreased. Therefore, the SO\textsubscript{2} removal rate by powdered AC increases slowly after 1.2 seconds.

Increasing the AC/S molar ratio increases the desulfurization efficiency of the powdered AC. When the AC/S molar ratio is increased from 100 to 345, the desulfurization rate by the powdered AC is increased from 28.11% to 70.24% at 1.2 seconds and is increased from 37.41% to 73.64% at 6.0 seconds, respectively. Increasing AC/S molar ratio indicates that the feed rate of the powdered AC is increased, the concentration of the powdered AC in flue gas is increased, more active sites are provided to adsorb SO\textsubscript{2}, and thereby the desulfurization efficiency is increased.

Increasing the AC/S molar ratio reduces the adsorption amount of SO\textsubscript{2} on the powdered AC. When the AC/S molar
ratio is increased from 100 to 345, the adsorption amount of SO$_2$ on the powdered AC is decreased from 12.87 mg/g to 9.23 mg/g at 1.2 seconds and is decreased from 17.13 mg/g to 10.11 mg/g at 6.0 seconds, respectively. When the AC/S molar ratio is 100, the concentration of the powdered AC in flue gas is lower and the concentration of SO$_2$ relative to the unit mass of powdered AC in flue gas is higher. The concentration difference between SO$_2$ in flue gas and SO$_2$ on the surface of the powdered AC is therefore increased and then the driving force for the powdered AC to adsorb SO$_2$ is also increased. When the AC/S molar ratio is 345, the concentration of the powdered AC in flue gas is higher and the competitive adsorption of SO$_2$ between the powdered ACs is increased, which reduces the adsorption quantity of SO$_2$ on the powdered AC. Zhan et al. have studied SO$_2$ removal by powdered AC in a CFB reactor and found that when the AC/S molar ratio increased, SO$_2$ removal efficiency increased rapidly, but SO$_2$ adsorption quantity decreased [11]. The research results of this paper are consistent with those of Zhang.

3.3. Influence of the Reaction Temperature on SO$_2$ Adsorption. The influence of the reaction temperature on the adsorption of SO$_2$ by powdered AC is shown in Figure 6. Increasing the reaction temperature reduces the desulfurization efficiency and the amount of SO$_2$ adsorbed by the powdered AC. When the reaction temperature is increased from 65°C to 95°C, the desulfurization rate by the powdered AC is decreased from 58.24% to 29.06% at 1.2 seconds and is decreased from 74.35% to 36.03% at 6.0 seconds, respectively. The amount of SO$_2$ adsorbed by the powdered AC is decreased from 10.74 mg/g to 5.36 mg/g at 1.2 seconds and is decreased from 13.71 mg/g to 6.64 mg/g at 6.0 seconds, respectively.

The AC/S molar ratio is 245 and SO$_2$, O$_2$, and H$_2$O concentration is 0.085%, 6%, and 8%. As shown in reaction equations (1)–(5), the powdered AC is used as adsorbent and catalyst to convert SO$_2$ into H$_2$SO$_4$. The adsorption of SO$_2$ and the catalytic oxidation of SO$_2$ to H$_2$SO$_4$ by the powdered AC are all affected by reaction temperature. From the perspective of adsorption, the adsorption of SO$_2$ in the gas phase on the solid surface is an instantaneous process. With the reduction of the free energy of the system, it also loses its degree of freedom, resulting in a reduction in enthalpy. Regardless of physical adsorption or chemical adsorption, the adsorption process is always exothermic. Therefore, increasing temperature is not conducive to the adsorption of SO$_2$ by the powdered AC. From the perspective of surface catalytic oxidation reaction, there is the breakage and formation of chemical bonds, which requires certain temperature conditions. Therefore, increasing temperature is conducive to the catalytic oxidation
reaction of SO$_2$ by the powdered AC. The temperature has a great influence on the physical adsorption of SO$_2$ by powdered AC. As the temperature increases, it reduces the physical adsorption of SO$_2$, which in turn affects the catalytic oxidation of SO$_2$ by the powdered AC. In addition, H$_2$O adsorption decreases with increasing temperature, and H$_2$SO$_4$ cannot be desorbed from the active sites in time [14].

### 3.4. Influence of SO$_2$ Concentration on SO$_2$ Adsorption

The influence of the concentration of SO$_2$ on the adsorption of SO$_2$ by powdered AC is shown in Figure 7. Increasing the concentration of SO$_2$ reduces the desulfurization efficiency of the powdered AC. When the concentration of SO$_2$ is increased from 0.015% to 0.05%, the desulfurization rate of the powdered AC is decreased from 86.02% to 74.13% at 1.2 seconds and is decreased from 94.67% to 77.25% at 6.0 seconds, respectively. When the concentration of SO$_2$ is increased, a part of SO$_2$ could not be adsorbed by the powdered AC and therefore the desulfurization efficiency is decreased.

The temperature is 65°C, AC feeding rate is 2.634 g/min, and O$_2$ and H$_2$O concentration is 6% and 8%.

Increasing the concentration of SO$_2$ increases the amount of SO$_2$ adsorbed by the powdered AC. When the concentration of SO$_2$ is increased from 0.015% to 0.05%, the
amount of SO\textsubscript{2} adsorbed by the powdered AC is increased from 2.80 mg/g to 8.03 mg/g at 1.2 seconds and is increased from 3.08 mg/g to 8.35 mg/g at 6.0 seconds, respectively. Increasing the concentration of SO\textsubscript{2} increases the concentration difference between SO\textsubscript{2} in flue gas and SO\textsubscript{2} on the surface of the powdered AC, and then the driving force for the powdered AC to adsorb SO\textsubscript{2} is also increased [15].

3.5. Influence of O\textsubscript{2} Concentration on SO\textsubscript{2} Adsorption. The influence of the concentration of O\textsubscript{2} on the adsorption of SO\textsubscript{2} by the powdered AC is shown in Figure 8. Increasing the concentration of O\textsubscript{2} increases the desulfurization efficiency and the amount of SO\textsubscript{2} adsorbed by the powdered AC. When the concentration of O\textsubscript{2} is increased from 0% to 6%, the desulfurization rate by the powdered AC is increased from 22.32% to 58.24% at 1.2 seconds and is increased from 25.76% to 74.35% at 6.0 seconds, respectively. The amount of SO\textsubscript{2} adsorbed by the powdered AC is increased from 4.06 mg/g to 10.74 mg/g at 1.2 seconds and is increased from 4.75 mg/g to 13.71 mg/g at 6.0 seconds, respectively.

There are two forms of adsorption of SO\textsubscript{2} on AC. One is weakly bonded SO\textsubscript{2}, which is easy to be desorbed at low temperature, corresponding to physically adsorbed SO\textsubscript{2} and the other is strongly bonded SO\textsubscript{2}, which can only be desorbed at high temperature, namely, SO\textsubscript{3}, which is related to the active sites of catalytic oxidation on AC surface [16]. Pinero et al. have found that, in the absence of O\textsubscript{2}, SO\textsubscript{2} was almost physical adsorption, and activated carbon materials could not oxidize SO\textsubscript{2} to SO\textsubscript{3} [16]. When the concentration of O\textsubscript{2} is 0%, SO\textsubscript{2} adsorbed on the surface of the powdered AC could not be oxidized to SO\textsubscript{3} and generated to H\textsubscript{2}SO\textsubscript{4}, which cannot empty the SO\textsubscript{3} adsorption center and hinder the adsorption of SO\textsubscript{2}. At this time, SO\textsubscript{2} mainly exists in the form of physical adsorption, with lower adsorption amount and lower desulfurization efficiency. When the concentration of O\textsubscript{2} increases, SO\textsubscript{2} adsorbed on the surface of the powdered AC is easily oxidized to SO\textsubscript{3}, which interacts with H\textsubscript{2}O to generate H\textsubscript{2}SO\textsubscript{4}, and H\textsubscript{2}SO\textsubscript{4} could be desorbed from the active center regenerated to further adsorb SO\textsubscript{2}, which increases the desulfurization efficiency and the amount of SO\textsubscript{2} adsorption.

3.6. Influence of H\textsubscript{2}O Concentration on SO\textsubscript{2} Adsorption. The influence of the concentration of H\textsubscript{2}O on the adsorption of SO\textsubscript{2} by the powdered AC is shown in Figure 9. Increasing the concentration of H\textsubscript{2}O increases the desulfurization efficiency and the amount of SO\textsubscript{2} adsorbed by the powdered AC. When the concentration of H\textsubscript{2}O is increased from 0% to 8%, the desulfurization rate by the powdered AC is increased from 23.18% to 58.24% at 1.2 seconds and is increased from 26.94% to 74.35% at 6.0 seconds, respectively. The amount of SO\textsubscript{2} adsorbed by the powdered AC is increased from 4.27 mg/g to 10.74 mg/g at 1.2 seconds and is increased from 4.97 mg/g to 13.71 mg/g at 6.0 seconds, respectively.

Mochida et al. have studied the continuous adsorption of SO\textsubscript{3} by AC fiber at low temperature, and the product was aqueous H\textsubscript{2}SO\textsubscript{4}. Mochida has found that larger H\textsubscript{2}O and O\textsubscript{2} concentrations in flue gas were conducive to the continuous removal of SO\textsubscript{2} in the form of aqueous H\textsubscript{2}SO\textsubscript{4}, and the rate control step was the aqueous H\textsubscript{2}SO\textsubscript{4} desorption from the surface of AC fiber [2]. When the volume fraction of H\textsubscript{2}O is 0%, SO\textsubscript{2} is oxidized to SO\textsubscript{3} by O\textsubscript{2} and SO\textsubscript{3} cannot be desorbed, which makes the active center invalid and cannot continue to adsorb SO\textsubscript{2}. When the volume fraction of H\textsubscript{2}O increases, SO\textsubscript{3} is easily combined with H\textsubscript{2}O to form H\textsubscript{2}SO\textsubscript{4} after SO\textsubscript{2} oxidized to SO\textsubscript{3} by O\textsubscript{2}. Excess H\textsubscript{2}O can elute H\textsubscript{2}SO\textsubscript{4} from the active center. The eluted H\textsubscript{2}SO\textsubscript{4} is stored in the micropores of the powdered AC, and the active center is regenerated to continue to adsorb and oxidize SO\textsubscript{2}. The increase of the volume fraction of H\textsubscript{2}O in flue gas has two main effects: on the one hand, the product SO\textsubscript{3} after SO\textsubscript{2}
oxidation is hydrated to H₂SO₄, and on the other hand, H₂SO₄ is eluted from the active center by excessive H₂O to regenerate active centers to facilitate the continuous adsorption of SO₂ [2, 7].

3.7. Influence of the Powdered AC Circulation Ratio on SO₂ Adsorption. The adsorption quantity of SO₂ is lower than the saturated adsorption capacity of SO₂ by the powdered AC under various working conditions [6, 15], so the recycling of the powdered AC plays a very important role in improving the desulfurization rate, reducing the amount of the powdered AC, and improving the utilization rate of the powdered AC. In order to study the cyclic adsorption performance of the powdered AC, a material receiving device is arranged at the outlet of the reactor to collect the powdered AC, which is defined as the first adsorption. And then the collected powdered AC is sent to the reactor according to a certain AC/S molar ratio to measure the desulfurization performance, and the powdered AC is collected again at the material receiving device, which is defined as the second adsorption, in turn until the adsorption of SO₂ is saturated. The influence of cyclic adsorption of the powdered AC on the adsorption of SO₂ is shown in Figure 10. When the cyclic adsorption is

![Figure 8](image_url)

Figure 8: Influence of O₂ concentration on (a) SO₂ removal rate and (b) SO₂ adsorption. The temperature is 65°C, AC/S molar ratio is 245, and SO₂ and H₂O concentration is 0.085% and 8%.

![Figure 9](image_url)

Figure 9: Influence of H₂O concentration on (a) SO₂ removal rate and (b) SO₂ adsorption. The temperature is 65°C, AC/S molar ratio is 245, and SO₂ and O₂ concentration is 0.085% and 6%.
increased from the first to the eighth, the desulfurization rate by the powdered AC is decreased slowly from 62.35% to 45.53%; after that, the decreasing trend of the desulfurization rate is accelerated, and the desulfurization rate is decreased to 6.83% at the fourteenth.

With the increase of cyclic adsorption, SO$_2$ adsorption amount increases, and then H$_2$SO$_4$ generated gradually increases. Because H$_2$SO$_4$ is stored in AC pores, H$_2$SO$_4$ occupies the active sites of AC, and the desulfurization rate decreases with cyclic adsorption increasing until the adsorption of SO$_2$ is saturated.

The circulation ratio refers to the ratio of the amount of material captured by the material separator and returned to the reactor to the amount of material supplied. In this paper, the influence of the circulation of the powdered AC on the desulfurization efficiency is simulated under the condition that the molar ratio of fresh powdered AC to SO$_2$ in flue gas is certain. The results are shown in Figure 10(b). Increasing the circulation ratio of the powdered AC increases the desulfurization efficiency. The desulfurization efficiency of the powdered AC is 62.35% when the powdered AC is not recycled. The desulfurization efficiency is increased to 99.42% when the circulation ratio of the powdered AC is 7. When the AC/S mole ratio is 300 and the powdered AC circulating ratio is 7, SO$_2$ can be removed effectively.

Increasing the circulation ratio of the powdered AC increases the concentration of AC in reactor and the number of active sites, which is conducive to the removal of SO$_2$.

3.8. The SO$_2$ Adsorption Kinetics. The Bangham model can be used to fit the adsorption process where multiple adsorption mechanisms exist, such as gas film diffusion, surface reaction, and intraparticle diffusion. This model was obtained by time compensated pseudo-first-order kinetics model, which made it have good adaptability in various adsorption processes. The Bangham model is shown in the following equation [17–19]:

\[ q_t = q_e \left( 1 - e^{-kt^n} \right), \]  

where $q_t$ is the adsorption amount of SO$_2$ on the powdered AC at time $t$, $q_e$ is the saturation adsorption capacity of SO$_2$ on the powdered AC, mg/g, and $k$ and $n$ are constants.

Figures 5(b), 6(b), 7(b), 8(b), and 9(b) show the fitting results of the Bangham model. Tables 2–6 show the parameters of the Bangham model. The calculated values of the Bangham adsorption kinetics model agree well with the experimental values, and the fitting correlation coefficient $R^2$ is higher, all of which are above 0.98. This indicates that SO$_2$
adsorption on the powdered AC in the drop tube furnace is controlled by multiple mechanisms, such as gas film diffusion, intragranule diffusion, and surface reaction. The SO$_2$ adsorption kinetics can be predicted by Bangham model.

4. Conclusions

The SO$_2$ adsorption kinetics on powdered AC was performed in a laboratory-scale drop tube furnace. The results show that the powdered AC rapidly adsorbs SO$_2$ in the initial 1.2 seconds and then the amount of SO$_2$ adsorption slowly increases. The SO$_2$ adsorption kinetics can be predicted by Bangham model.

The SO$_2$ removal rate increases with the increasing of AC/S molar ratio, the decreasing of adsorption temperature, and inlet SO$_2$ concentration. The adsorption amount of SO$_2$ by the powdered AC increases with the increasing of the inlet SO$_2$ concentration, the decreasing of AC molar ratio, and adsorption temperature. The O$_2$ and H$_2$O are beneficial to SO$_2$ removal by the powdered AC.

The recycling of the powdered AC plays a very important role in improving the desulfurization rate, reducing the amount of the powdered AC and improving the utilization rate of the powdered AC. SO$_2$ removal rate drops to 6.83% after 14 cyclic adsorptions. The powdered AC circulation increases SO$_2$ removal rate from 62.35% to 99.42% with AC circulation ratio = 7.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Table 5: The parameters of Bangham model of Figure 8(b).

| O$_2$ concentration (%) | 0   | 2   | 4   | 6   |
|------------------------|-----|-----|-----|-----|
| $q_e$ (mg/g)           | 5.0 | 8.9 | 11.1| 14.9|
| $K$                    | 1.54| 1.84| 1.88| 1.13|
| $N$                    | 0.35| 0.29| 0.41| 0.38|
| $R^2$                  | 0.999| 0.999| 0.998| 0.993|

Table 6: The parameters of Bangham model of Figure 9(b).

| H$_2$O concentration (%) | 0   | 3   | 8   |
|--------------------------|-----|-----|-----|
| $q_e$ (mg/g)             | 5.2 | 10.6| 14.9|
| $K$                      | 1.58| 1.61| 1.13|
| $N$                      | 0.34| 0.35| 0.38|
| $R^2$                    | 0.993| 0.999| 0.993|

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