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Research Article

Effects of Metamorphic Degree of Coal on Coal Dust Wettability and Dust-Suppression Efficiency via Spraying

Pengfei Wang ,[1,2,3] Han Han,[1] Ronghua Liu,[1] Yongjun Li,[1] and Xuanhao Tan[1]

[1]*School of Resource, Environment & Safety Engineering, Hunan University of Science & Technology, Xiangtan 411201, China*
[2]*Work Safety Key Lab on Prevention and Control of Gas and Roof Disasters for Southern Coal Mines, Hunan University of Science & Technology, Xiangtan 411201, China*
[3]*Department of Civil and Architectural Engineering and Mechanic, University of Arizona, Tucson, AZ 85721, USA*

Correspondence should be addressed to Pengfei Wang; pfwang@sina.cn

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Currently, spraying is a main means for dust prevention and control in underground coal mines. The dust-suppression efficiency via spraying is highly correlated with the wettability of coal dusts. There are many factors affecting the wettability of coal dust, among which coal's metamorphic degree has great influence. In order to gain in-depth knowledge of the effects of coal metamorphic degree on coal dust wettability and the dust-suppression efficiency via spraying, 6 coal dust samples with different metamorphic degrees were collected and used in the study. In the experiments, the microproperties, wetting performance, and dust-suppression efficiency via spraying were measured. According to the experimental results of coal's microproperties, with the improvement of metamorphic degree, the content of hydrophilic oxygen-containing functional groups on the surface, the surface roughness, the specific surface area, and the interpore diameter all decreased. In addition, as coal's metamorphic degree was enhanced from lignite to meager-lean coal, the wettability of the coal dust dropped. On the other hand, as the metamorphic degree of coal quality continued to be improved to anthracite, the wettability of the coal dust increased instead. The measured results revealed that the dust-suppression efficiency via spraying was highly correlated with the wettability of coal dust. The coal dust with better wettability exhibited higher dust-suppression efficiency via spraying. With the increase of water-supply pressure, the effect of coal dust wettability on the dust-suppression efficiency via spraying was weakened, and the difference of dust-suppression efficiency among different coal dust samples was narrowed.

1. Introduction

Coal is an important natural resource and plays a decisive role in the development of national economy [1–4]. During underground coal mining and transportation processes, a great amount of coal dust is produced [5–7]. Without effective control, coal dust not only threatens workers' physical health but also causes serious threat to the safe production in coal mines [8–12]. According to China's occupational disease report released by the National Health Commission in the People's Republic of China, 23,497 occupational cases were reported in 2018, among which 19,468 patients suffered from pneumoconiosis, occupying 82.85% of total occupational cases [13]. In terms of industrial distribution of the occupational disease, the newly reported pneumoconiosis cases were mainly distributed in coal mining and nonferrous metal mining industries. In particular, the number of pneumoconiosis cases in coal mining industry accounts for 40% of the total number of the reported occupational cases. Therefore, it is extremely urgent to adopt high-efficiency dust-suppression and dust-control measures to reduce the dust concentration in coal production sites [14–18].

Currently, the main dust prevention methods in underground coal mine include preinjection of water into coal, ventilation, exhausting of dust, purification of air by dust remover, spraying, and dust isolation via enclosing [19–25]. Spraying has been extensively applied in underground mines for dedusting due to the low cost, convenient operation, and practicability [26–31]. The results in previous studies also revealed that the dust-suppression efficiency via spraying was closely related to the wettability of the coal dust. In general, spraying has higher dust-suppression performance on the coal dust with more favorable wettability. Hydrophobic coal dust can hardly be combined with the droplets in the air and can only be captured by a large number of droplets at high movement velocity [32–39]. Therefore, the in-depth knowledge of the wettability of coal dust and the dust-suppression efficiency via spraying has great guiding significance for the design of dust-suppression scheme via spraying and the prediction of dust-suppression efficiency in underground coal mines.

For the above reasons, researchers have performed many studies on the wettability of coal dust. Using Dataphysics DCAT21 surface interface tension meter, Dong et al. [40] measured the contact angles of 5 different types of ultrafine coal powders with different metamorphic degrees and found that the surface of coal dust became super-hydrophobic after ultrafine crushing. Wen et al. [41] adopted the software of MDI Jade 6.5 to analyze the inorganic mineral characteristics of the ashes in coal dust and investigate the effect of inorganic minerals on the dust wettability. From the results, quartz in coal dust ash can be used as the evaluation index of the hydrophily of coal dust. Chen et al. [42] examined the functional groups on the surface of coal dust using Fourier transform infrared (FTIR) spectrometer and pointed out that the wettability of the coal dust was affected by the transmittance of aromatic ring C-H stretching at 3050 cm^{-1}, the transmittance of S-O-Si antisymmetric stretching at 1020–1100 cm^{-1}, and the content of Zhao et al. [43] investigated the relations of coal dust wettability with the quality parameters of coal and the functional groups on the surface of coal dust using experiments. In their study, a method was developed to measure and characterize the wettability of coal dust rapidly. Zhou et al. [44, 45] examined the carbon skeleton structures of coal dust particles with 6 different metamorphic degrees using magnetic resonance imaging (MRI) and revealed the variation patterns of the structural parameters for aromatic carbon and fat carbon with metamorphic degree. Luo et al. [46] investigated the influence of the chemical composition and internal structural parameters of the coal dust on the wettability. It was concluded that the chemical composition of coal dust played a dominant role in causing the difference in wettability. The carbon content and oxygen content played a significant role in the wettability of coal dust, while the average pore size and specific pore volume of the particles were less correlated with the wettability of coal dust. Huang et al. [47] conducted industrial analysis and elemental analysis on 13 types of coal dust with different metamorphic degrees. The wettability of each type of coal dust was measured using reverse osmosis experiment. On this basis, the optimal regression equation for the chemical composition of coal dust with the wettability of coal dust was established using both linear and nonlinear regression methods. The optimal regression equation can be used to determine the most significant influencing factors for the wettability of coal dust. In the study by Wang et al. [48], the functional group composition and wettability of five types of coal dust were obtained through infrared spectroscopy and contact angle experiments. The hydrophilic functional groups and hydrophobic functional groups on the surface of coal dust were determined. In addition, the coal dust with different degrees of metamorphism was evaluated to have different wettability.

Based on the relationship between the chemical composition and wettability of coal dust, Yang et al. [49, 50], Zhou et al. [51], and Wen and Liu [52] systematically investigated the effects of particle size of coal dust on the surface properties and wettability. The experimental methods included FTIR spectroscopy, X-ray photoelectron spectroscopy, and contact angle measurement. The results showed that the surface pore structure, chemical structure, and element composition of coal dust all changed with the reduction in the particle size of coal dust. In addition, as the particle size decreased, the wettability became weaker while the hydrophobicity became stronger. Some researchers have also investigated the effect of surface roughness of coal dust on the wettability. However, the obtained conclusions by these researchers on this topic were different and even contrary [53–56]. At present, regarding the influence of the surface roughness on the wettability of coal dust, the accepted conclusion is that as the surface of coal dust gets rougher, the wettability is better [57, 58].

Up to now, there has been a great progress in the studies on the wettability of coal dust, especially in the influence mechanism of the chemical composition and the metamorphic degree on the wettability of coal dust. However, there are two problems in the previous studies: (1) The method of determining the wettability of coal dust is relatively simple. Only a single index, i.e., contact angle or reverse osmosis moisture, was used to evaluate the wettability. Thus the accuracy of the conclusion needs to be further verified. (2) The studies only investigated the influence of the metamorphic degree of coal dust on the wettability. However, the correlation between the wettability and the dust-reduction efficiency via spraying was not analyzed. Thus the effect of the metamorphic degree on the dust-reduction efficiency of coal dust still needs to be determined. In this study, coal dust particles with 6 different metamorphic degrees were collected from the main coal production sites in China. In addition, infrared (IR) spectra, BET measurement, and scanning electron microscope (SEM) were used to analyze the microstructure of coal dust. Based on the combination of the contact angle and reserve osmosis experiments, the influence mechanism of the metamorphic degree on the wettability of coal dust was analyzed on a microscopic level. On this basis, the custom-developed dust-suppression experimental platform via spraying was used to investigate the dust-suppression efficiencies for the coal dust particles with different metamorphic degrees. The effect of the metamorphic degree of coal dust on the dust-suppression efficiency via spraying was evaluated. The results in this study can provide insightful reference and guidance for the design of spraying-based dust-suppression scheme and theoretical prediction of dust-suppression efficiency via spraying in underground coal mines.

2. Experimental Samples and Scheme

2.1. Experimental Samples. In order to obtain thorough knowledge about the influence of the metamorphic degree on the wettability of coal dust, coal dust particles with 6 different metamorphic degrees were collected from the main coal production sites in China. Specifically, the samples can be arranged in the following order according to the ascending of the metamorphic degree: lignite sample from Donghuai Coal Mine, Guangxi, gas coal sample from Baodian Coal Mine, Shandong, fat coal sample from Qianjiaying Coal Mine, Hebei, coking coal sample from Wanfeng Coal Mine, Shanxi, Meager-lean coal sample from Fa'er Coal Mine, Guizhou, and anthracite sample from Motian Coal Mine, Hunan. The industrial indexes and characteristic particle sizes of these 6 coal samples are listed in Table 1.

The collected coal samples were crushed by the grinder and sieved by standard industrial sifter with the pore diameter of 100 meshes. The sieved coal dust samples were labeled in the ascending order of metamorphic degree and placed in a vacuum drying oven for 480 minutes at 80°C. After being dried, the samples were placed in the sealing bag for further analysis. The particle size of coal dust was measured by LS13320 laser particle size analyzer. The measured results are shown in Figure 1.

2.2. Measurement of Basic Properties of Coal Dust. The basic properties of coal dust consisted of two parts, i.e., the microproperties and the wetting performance. The first group of experiments analyzed the microproperties of coal dust. Previous studies demonstrated that the wettability of coal dust was mainly affected by the important intrinsic parameters, including functional groups on the surface of coal dust, specific surface area, and mean internal pore diameter. The function groups on the surface of the moulded sample were analyzed using a Nicolet 6700 FT-IR spectrometer. Surface roughness of the coal sample was characterized by a new-generation high-resolution SEM (SU3500, Hitachi, Japan). Specific surface areas and mean pore diameters of the 6 coal dust samples were measured by the BET analyzer (ASAP2010, Micromeritics, America).

The second group of experiments investigated the wetting performance of coal dust. In this study, wetting performance of coal dust was evaluated by the contact angle and the reverse osmosis hygroscopic capacity. 400 mg coal powder was added to the mould and placed under a bench powder compressing machine. The moulding pressure with a magnitude of 50 MPa was applied and maintained for 1 minute to prepare the cylindrical test piece with the thickness of 2 mm. Three test pieces with smooth surfaces were prepared for each coal dust sample. The contact angle between distilled water and the test piece of coal dust was then measured by a CA100B contact angle meter. For each coal dust sample, the contact angle was measured from 3 test pieces and the average results were obtained. The hygroscopic properties of the prepared coal dust sample were measured using the custom-designed reserve osmosis device. Three grams of coal sample was placed in a glass tube with a diameter of 10 mm, and the tube was sealed by the filter paper and weighed. The glass tube was then inversed and placed into a water tank. Distilled water was added to the tank until it exactly submerged the orifice of the glass tube. After 10 minutes, the tube was taken out and weighed to calculate the water absorption capacity of the coal dust.

2.3. Measurement of Dust-Suppression Efficiency via Spraying. As shown in Figure 2, a dust-suppression experimental system via spraying was designed to simulate dust production, spraying, and ventilation conditions. The system mainly consisted of the tunnel model, a high-pressure water pump, a water tank, a control box, an aerosol generator, and the related pipes, valves, and measurement instruments. The tunnel model mainly included an inlet section, a measurement section, a spraying section, an axial flow fan, and an outlet section. The main section of the roadway model was 30 m, in which the length of the spraying section was 10 m. The section of the roadway was rectangular with the dimension of 60 cm × 60 cm. To facilitate the measurement of droplet size using the Malvern particle size analyzer, the main section of the tunnel model was made of the transparent organic glass with the thickness of 1 cm.

In this study, dust was generated by a dry-powder aerosol diffuser (AG420, Germany) at the rate of 13 g/min. Two antiexplosion dust samplers (FCC-25) were arranged in the measurement section. One sampler was placed in front of the spraying system and the other one was placed behind the spraying system. Dust particles at both measurement points were simultaneously collected under different operating conditions. Under each operating condition, the sampling was continuously conducted 3 times and the average value was calculated. The sampling time was set to 2 minutes and the sampling rate was set to 15 L/min. The mass concentration of dust was calculated from the weight measured by an electronic analytical balance. Before the test of dust-suppression efficiency via spraying, the airflow velocity in the tunnel model was set to 1.0 m/s. The dust-suppression efficiencies for 6 different types of coal dust samples were measured under 4 different water supply pressures, i.e., 0.5 MPa, 1.0 MPa, 1.5 MPa, and 2.0 MPa. A commonly used nozzle in mines, i.e., the spiral-apertured pressure nozzle with the outlet diameter of 0.8 mm, was used in the experiment. Figure 3 shows the structure of the spiral-apertured pressure nozzle. The water in the dust-reduction experiment via spraying was from the municipal pipe network. The droplet size parameters under 4 different water supply pressures were measured using Malvern particle size analyzer.

The horizontal droplet flow can be divided into a diffusion section, a direct-injection section, and an attenuating section. In the diffusion section, located near the exit of the nozzle, the droplets are dense and the particle size changes dramatically. Thus, in the diffusion section, the penetration of the transmitted laser from the Malvern

Table 1: Industrial analysis indexes and characteristic particle sizes of experimental coal samples.

No.	Coal property	Mad (%)	Aad (%)	Vad (%)	FCad (%)	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
1	Lignite	1.59	10.75	39.87	49.79	21.43	109.53	171.05
2	Gas coal	2.02	10.27	34.02	53.69	32.01	123.98	234.30
3	Fat coal	2.36	10.87	34.42	56.71	11.86	100.89	205.79
4	Coking coal	2.56	12.72	14.94	69.78	6.52	76.19	195.27
5	Meager-lean	3.56	13.18	15.39	67.87	20.79	111.91	231.72
6	Anthracite	3.25	23.50	5.10	68.15	7.98	81.86	215.41

Note: "Mad" refers to the content of air-dried moisture in the air, "Aad" refers to the content of air-dried ash in the air, "Vad" refers to the content of air-dried volatile in the air, and "FCad" refers to the content of fix carbon. D_{10}, D_{50}, and D_{90} are characteristic particle diameters, i.e., the volume of the particles with the diameters below D_{10}, D_{50}, and D_{90} occupy 10%, 50%, and 90% of total particle volume, respectively.

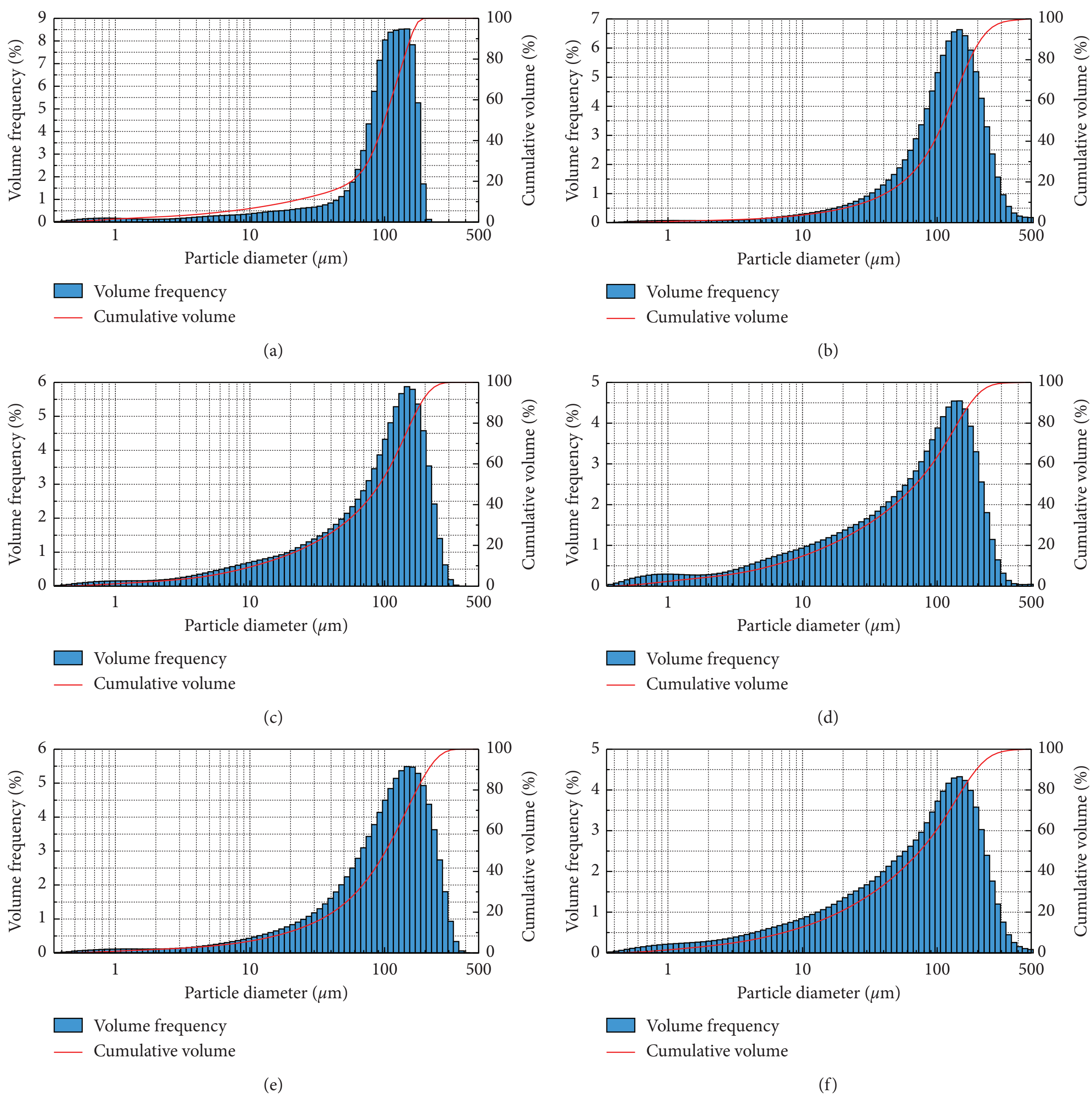

Figure 1: Particle size distribution of experimental coal samples: (a) lignite; (b) gas coal; (c) fat coal; (d) coking coal; (e) meager-lean coal; (f) anthracite.

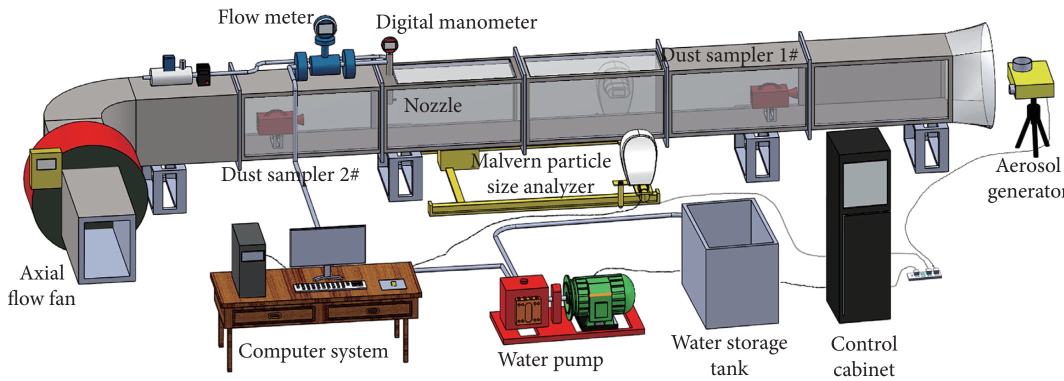

FIGURE 2: Dust-suppression experimental system via spraying.

FIGURE 3: Structure of the spiral-apertured pressure nozzle.

droplet size analyzer is limited while the receiver has challenges to detect the signal and measure the droplet size. In the attenuation section, the droplet flow has an irregular shape and the distribution of the droplets is significantly affected by gravity. Therefore, in this study, the direct-injection section of the droplet flow is selected for the data acquisition to measure the parameters of droplets. The specific position for data acquisition was located at the center of the vertical cross section, which was 50 cm downstream of the nozzle.

3. Experimental Results and Analysis

3.1. Microproperties of Coal Dust. In order to illustrate the influence mechanism of the internal structure of coal dust on the wettability, many microcharacteristic parameters were acquired in the test, including surface functional groups, surface roughness degrees, specific surface areas, and internal pore diameters of coal dust samples with different metamorphic degrees.

3.1.1. Surface Functional Groups. Figure 4 shows the IR spectra of coal dust samples with 6 different metamorphic degrees in the study. In Figure 4, the absorption peaks can be clearly observed at 3400–3500 cm^{-1}, 2800–3000 cm^{-1}, 1600–1620 cm^{-1}, and 1020–1100 cm^{-1}. The above 4 absorption peaks are corresponding to the stretching radicals of aromatic hydroxyl, the absorption peak of C-H stretching radicals of aliphatic series, the absorption peak of C-H stretching radicals of aromatic ring, and the absorption peak of antisymmetrical stretching of Si-O-Si in quartz, respectively. Based on the results, despite of different metamorphic degrees, the 6 coal dust samples exhibited similar spectral pattern and almost identical characteristic peaks, which indicated that the coal dust samples had similar internal structure. Meanwhile, due to the differences in the metamorphic degree and the coal-formation condition, the characteristic absorptions of the 6 coal dust samples differed at the same wave length to a certain degree.

By comparing and analyzing IR spectra of different coal dust samples, the transmittances at the characteristic peaks were greatly different among the coal dust samples with different metamorphic degrees. Overall, the transmittance increased with the increase of metamorphic degree. Previous studies demonstrate that the wettability of coal dust was highly correlated with the oxygen-containing functional groups on the surface of coal dust, including aliphatic hydrocarbon and aromatic hydrocarbon [59, 60]. In general, the coal dust with a higher content of oxygen-containing functional groups is more hydrophilic and exhibits more favorable wettability. Therefore, the oxygen-containing functional groups corresponding to above 4 characteristic peaks were selected for in-depth analysis. The IR spectra were interpreted into absorbance based on Lambert-Beer Law. Then both heights and areas of the characteristic peaks of the oxygen-containing functional groups were quantitatively analyzed using OMNIC 8.0. The analysis results are shown in Figure 5.

As shown in Figure 5(a), the height of the characteristic peak decreased steadily with the increase of metamorphic degree, which suggested that the content of oxygen-containing functional groups gradually decreased with the coal-formation time and the environmental evolution. The coal sample with higher metamorphic degree contained a smaller content of oxygen-containing functional groups. The characteristic peaks of the oxygen-containing functional groups of lignite sample were highest while those of anthracite sample were lowest. From Figures 5(b) and 5(c), the areas at 4 characteristic peaks decreased steadily with the improvement of coal quality. The results further confirmed that, with the increase of the metamorphic degree, the oxygen-containing functional groups on the surface gradually fell off, resulting in the decrease of the content of oxygen-containing functional groups.

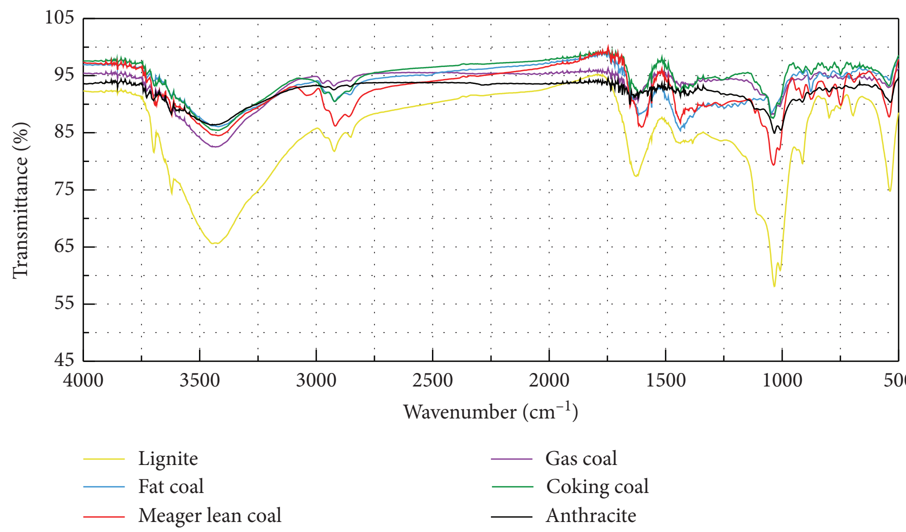

Figure 4: IR spectra of different coal dust samples.

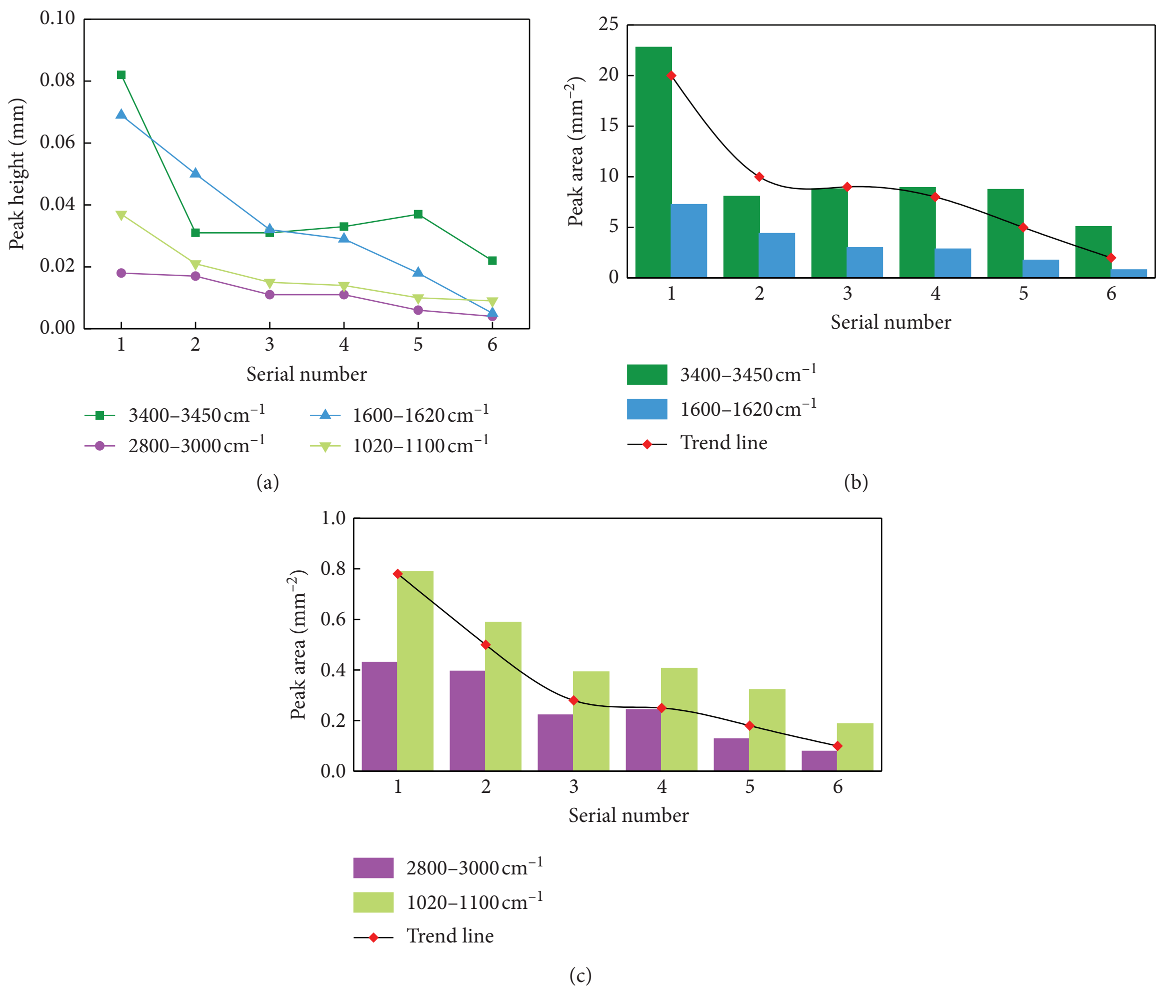

Figure 5: Heights and areas of the characteristic peaks of the oxygen-containing functional groups: (a) heights of the characteristic peaks; (b) areas at the characteristic peaks of 3400–3450 cm^{-1} and 1600–1620 cm^{-1}; (c) areas at the characteristic peaks of 2800–3000 cm^{-1} and 1020–1100 cm^{-1}.

3.1.2. Surface Characteristics and Internal Pore Diameter of Coal Dust. Previous studies suggested that the roughness degree on the surface of the material affected the wettability to a certain degree. In general, for nonhydrophobic material with a contact angle of below 90°, a rougher surface is indicative of more favorable wetting performance [57, 58]. Figure 6 shows the SEM images of the 6 coal dust samples. From Figure 6, due to the differences in metamorphic degree and the coal formation condition, 6 coal samples exhibited different surface characteristics. To be specific, lignite sample and gas coal sample had rough surfaces with a great number of convex-concave points and pores. Fat coal sample, coking coal sample, and meager-lean coal sample had smooth surfaces but a lot of gullies. Anthracite sample had the smoothest surface without obvious voids and bumping points. Therefore, the coal sample with a better metamorphic degree exhibited a smoother surface.

After the coal sample was crushed into coal dust, the dust surface was irregular, rugged, and simultaneously containing many well-developed pores. The specific surface area of coal dust and internal pores had influence on the wetting performance. The specific surface areas and the pore diameter distributions of the 6 different types of coal dust particles were measured by nitrogen adsorption method. The measurement results are shown in Figure 7. Overall, the specific surface area of the coal dust decreased with the improvement of coal quality. Under same crushing conditions, in spite of roughly identical particle sizes, the coal sample with better quality had smoother surface, uniformly distributed surface patterns, and smaller specific surface area. This phenomenon was because of different hardness degrees and densities of the coal dust sample. In general, the wettability of the coal dust is worse when the surface of the coal dust is smoother, the morphology distribution is more uniform, and the specific surface area is smaller. Meanwhile, it can be easily observed that mean pore diameter of the coal sample also decreased with the enhancement of coal quality. Among the 6 tested samples, anthracite sample and lignite sample had smallest and greatest mean pore diameters, respectively. This was consistent with the results from SEM images. Since the anthracite coal had smooth surface and no obvious fractures, the mean pore diameter of the anthracite sample was small. By contrast, lignite sample was characterized by uneven surface and a great number of pores; thus a lot of new pores were produced after being crushed. Therefore, the mean internal pore diameter of the crushed lignite sample was great.

3.2. Measurement of Coal Dust Wettability

3.2.1. Contact Angle Test. When the droplet is in contact with the solid surface, a gas-solid-liquid interface is formed, and the intersection angle between solid-liquid interface and gas-liquid interface is called contact angle. Contact angle is an important index to characterize the wetting performance of solid materials. Due to the difference in metamorphic degree, both physical and chemical properties were different among different coal dust samples. The coal dust samples with different metamorphic degrees had different abilities combined with droplets. As a result, different coal dust samples exhibited different wetting performances. In this study, the contact angles between the distilled water and different test pieces of coal dust were measured by a CA100 B contact angle meter. The measured results are shown in Figure 8.

From Figure 8, lignite sample had the smallest contact angle, and the mean value of three measurements was 25.28°. The results proved that lignite sample had the best wettability. With the improvement of metamorphic degree, the contact angles of gas coal sample, fat coal sample, coking coal sample, and meager-lean coal increased gradually. The contact angle of meager-lean coal was the greatest, and the mean value of three measurements was over 80°. The results suggested that the wettability of coal dust decreased gradually with the improvement of the quality of coal. Figure 9 shows the projection of the contact angles of 6 types of coal dust samples, which indicated that all the coal dust samples exhibited similar variation trends. This phenomenon was due to the fact that, with the enhancement of metamorphic degree, although the content of fixed carbon in coal dust was increased, the content of oxygen-containing functional groups on the surface, the surface roughness, and the internal pore diameter were all decreased. For anthracite, since the quality of the coal was improved, the measured contact angle decreased. As a result, the wettability of the anthracite sample was improved. Although anthracite sample had a high coalification degree, it only contained a small number of oxygen-containing functional groups on the surface and the surface was smooth. However, as listed in Table 1 (industrial analysis results of coal samples), the ash content of anthracite was as high as 23.5%, which was significantly higher than that of the rest 5 coal dust samples. According to the results in the previous relevant studies, inorganic minerals in coal dust ash significantly affected the wettability [52]. Under the same conditions, the coal sample with higher ash content exhibited more favorable wettability. Therefore, because of greater ash content, the wettability of anthracite sample was remarkably improved. The contact angle of anthracite was smaller than that of meager-lean coal but was slightly greater than that of lignite. Thus in term of wettability, anthracite ranked second among the 6 coal samples. In conclusion, the wettability of coal dust was influenced by a lot of factors, including the content of fixed carbon, the content of oxygen-containing functional groups, the ash content, and the surface structural characteristics. In other words, the wettability of coal dust is the result of the combined actions by multiple factors.

In previous studies, it was demonstrated that there existed a certain relationship between the wettability of coal dust and the content of oxygen-containing functional groups when the ash content was fixed [44, 45]. As listed in Table 1, except the anthracite sample, the other 5 coal dust samples had similar ash contents. Therefore, these 5 anthracite coal dust samples were selected for further analysis. The relationship between the areas of the characteristic peaks corresponding to two representative oxygen-containing

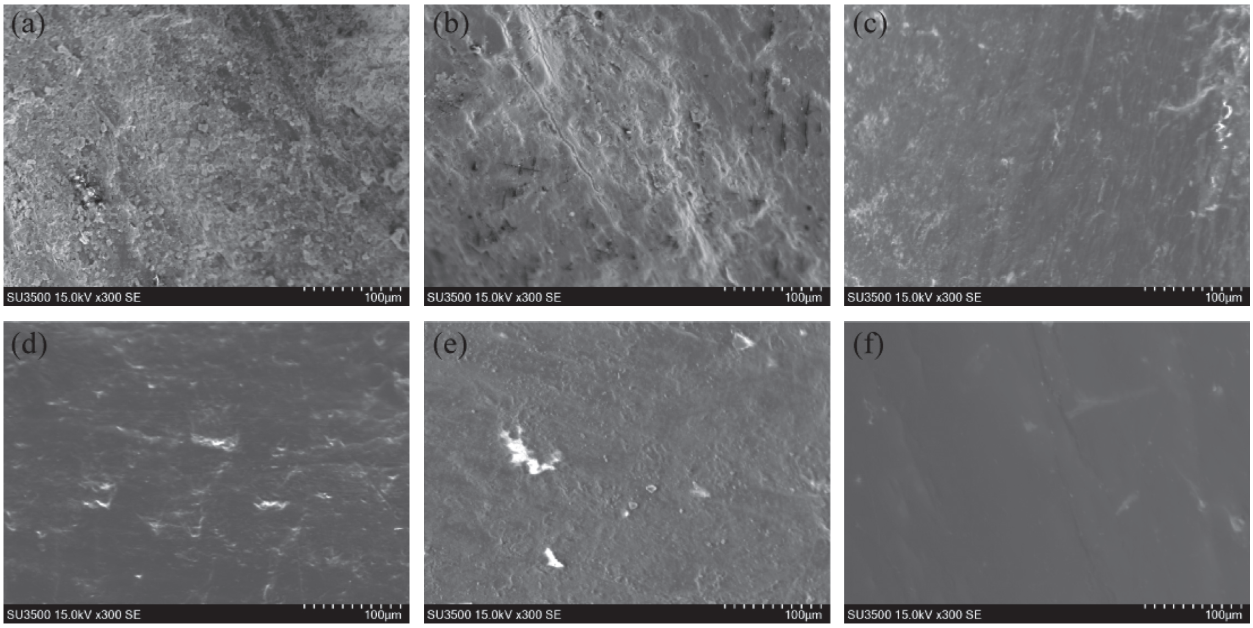

Figure 6: SEM images of different coal samples at a magnification factor of 300: (a) lignite; (b) gas coal; (c) fat coal; (d) coking coal; (e) meager-lean coal; (f) anthracite.

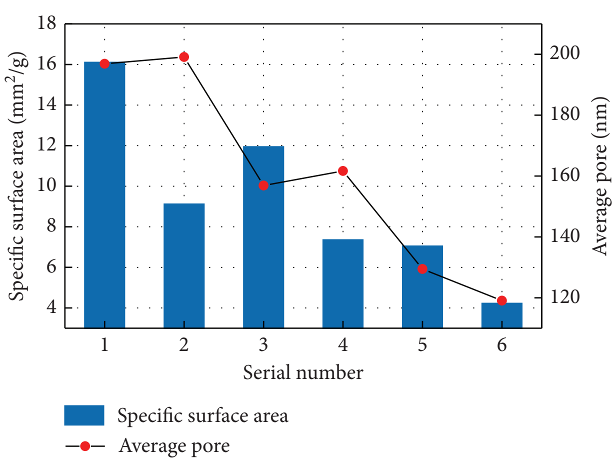

Figure 7: Specific surface area and mean pore diameter of coal samples with different metamorphic degrees.

functional groups and the measured contact angle was fitted, as shown in Figure 10.

In Figure 10, the measured contact angle of coal dust decreased with the increase of the area of the characteristic peak corresponding to the oxygen-containing functional groups. A greater area of the characteristic peak corresponding to the oxygen-containing functional group was indicative of a smaller contact angle and more favorable wettability of coal dust. According to the fitted results, the areas of the characteristic peaks of the oxygen-containing functional group were linearly correlated with the measured contact angle. At both characteristic peaks, the correlation coefficients of the fitting curve were 0.9394 and 0.8369, respectively. Therefore, for coal dust samples with similar ash contents in industrial analysis indexes, the wettability can be qualitatively and quantitatively assessed by the areas of the characteristic peaks corresponding to the oxygen-containing functional groups on the surface.

3.2.2. Reverse Osmosis Test. Reverse osmosis is a conventional method to measure the wetting properties of powder materials based on the principle of capillary. In this study, the custom-designed reverse osmosis hygroscopic capacity measurement equipment was used to measure the hygroscopic capacities of the above 6 different types of coal dust samples within the prescribed time. The measurement results are shown in Figure 11.

In Figure 11, the lignite sample has the greatest hygroscopic capacity (680.10 mg), while the meager-lean coal sample and coking coal sample had the lowest hygroscopic capacities, which were 19.75 mg and 18.95 mg, respectively. According to the measured hydroscopic capacities in the reverse osmosis test, lignite with the lowest metamorphic degree exhibited the most favorable wettability, while meager-lean and coking coal samples with high metamorphic degrees had poor wettability. Due to the high ash content, the wettability of anthracite coal sample was improved, and the hygroscopic capacity of anthracite was second only to that of lignite. Thus, the hygroscopic capacity gradually decreased with the increase of the metamorphic degree of coal. As the rank of coal increased from lignite sample to meager-lean coal sample, the hygroscopic capacity gradually decreased, and the wettability of coal continuously decreased. As the quality of coal was enhanced to anthracite sample, the wettability was enhanced. The consistent results from both the contact angle and the hydroscopic capacity have proved that the conclusions on the wettability of coal dust are accurate and reliable.

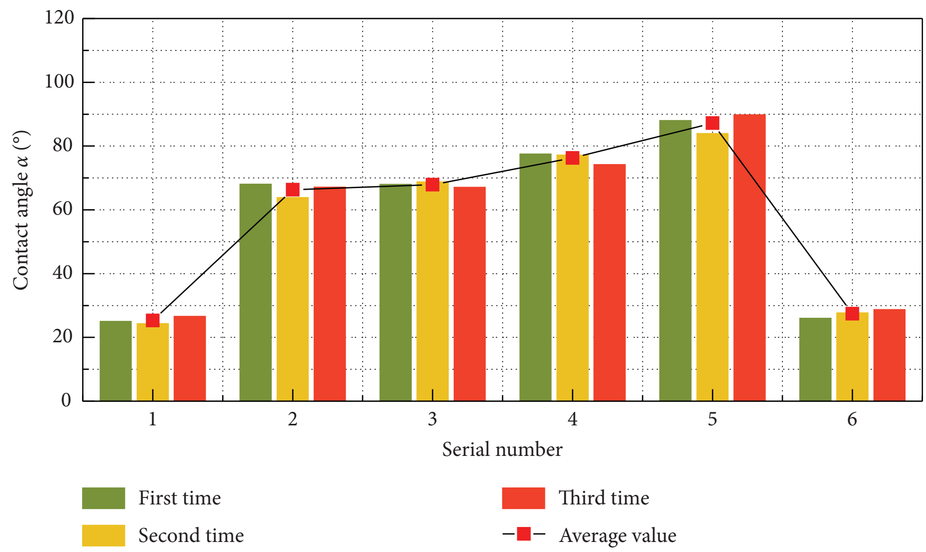

Figure 8: Measured contact angles of different coal dust samples.

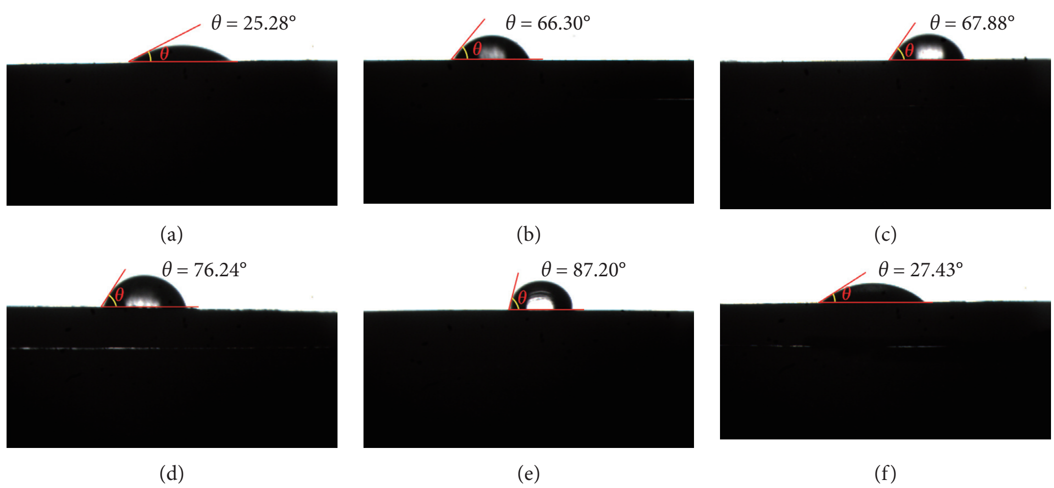

Figure 9: Measured contact angles for different coal samples: (a) lignite, (b) gas coal, (c) fat coal, (d) coking coal, (e) meager-lean coal, and (f) anthracite.

3.3. Dust-Suppression Experiment via Spraying

3.3.1. Atomization Characteristics of the Nozzle. The dust-suppression efficiency via spraying is highly correlated with the atomization characteristics of the nozzle. In order to obtain the relationship between the wettability of coal dust and the dust-suppression efficiency via spraying, the atomization characteristics were measured under four different water-supply pressures. The measurement results are shown in Table 2.

Overall, with the increase of water-supply pressure, both the flow rate of the nozzle and the volume concentration of droplets increased steadily. As a result, the capacity of atomizing water in unit space was increased, which can improve the collection of dust particles. It can also be observed from Table 2 that all the characteristic particle sizes of droplets, i.e., D_{10}, D_{50}, D_{90}, $D_{[3,2]}$, and $D_{[4,3]}$ decreased with the increase of water-supply pressure. At a water supply pressure of 0.50 MPa, $D_{[3,2]}$ was 145.8 μm; as water supply pressure increased to 1.0 MPa, 1.5 MPa, and 2.0 MPa, $D_{[3,2]}$ decreased to 132.6 μm, 117.6 μm, and 106.6 μm, respectively. Figure 12 shows the distribution of droplet particle sizes under four different water-supply pressures. From the histograms in the figure, with the increase of water-supply pressure, the peak of the volume frequency shifted towards the left, indicating the decreasing of droplet size. According to the cumulative volume fraction, the characteristic sizes of droplets, i.e., D_{90}, D_{50}, and D_{10}, all decreased with the increase of water supply pressure.

3.3.2. Dust-Suppression Efficiency via Spraying. Coal samples with different metamorphic degrees have different wettability of coal dust. In order to investigate the relationship between the wettability of coal dust and the dust-suppression efficiency via spraying, the dust-suppression

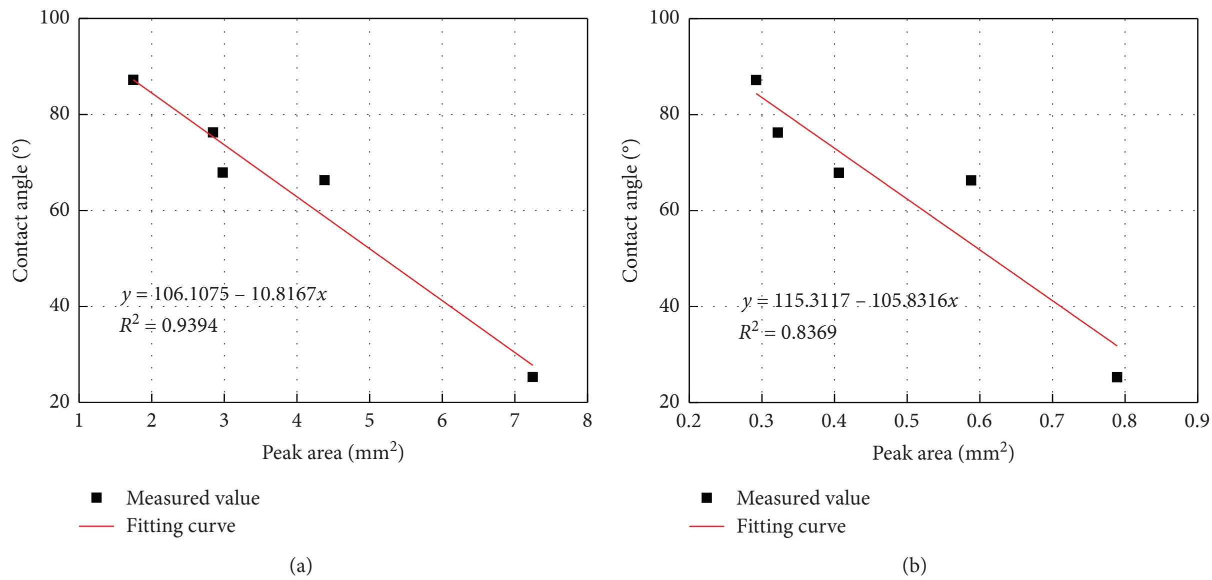

Figure 10: Relationship between the measured contact angle and the areas of the characteristic peaks: (a) 1600–1620 cm^{-1}; (b) 1020–1110 cm^{-1}.

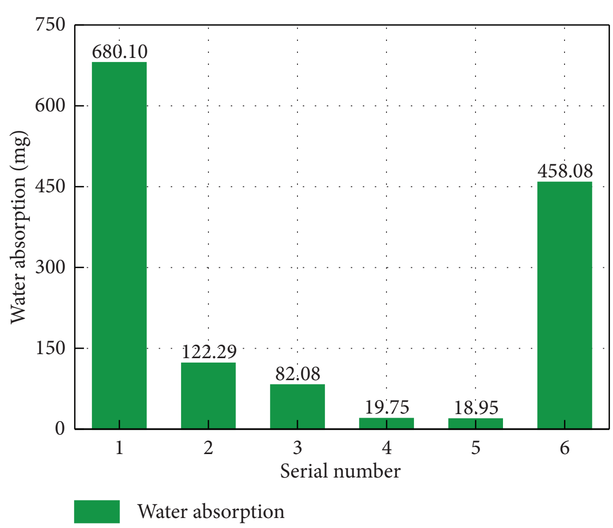

Figure 11: Water absorptions of different coal dust samples.

experiment was conducted on coal dust samples with different metamorphic degrees. The experimental results are shown in Figure 13.

In Figure 13, under the same water-supply pressure, the dust-suppression efficiency via spraying decreases with the increase of the metamorphic degree of coal. As the quality of coal was enhanced to anthracite, the dust-suppression efficiency via spraying was enhanced. The measured dust-suppression efficiencies agreed well with the experimental results of the wettability of coal dust described in the above sections. Under similar spraying conditions, the dust-suppression efficiency for the coal dust particles with similar sizes was closely related to the wettability of the coal dust. The coal dust particles with better wettability had stronger ability to combine with droplets, which enhanced the dust-suppression efficiency via spraying. According to the above results, anthracite sample ranked only second to lignite sample in terms of wettability. However, according to the measured results, the dust-suppression efficiency of anthracite sample was slightly lower than that of gas coal sample. Anthracite sample ranked third in dust-suppression efficiency. This may be attributed to the nonidentical particle sizes of above 6 coal dust samples. As shown in Table 1, the characteristic size of anthracite sample ($D_{50} = 81.86\,\mu$m) was significantly smaller than that of gas coal sample ($D_{50} = 121.98\,\mu$m). In general, smaller coal dust particles are more difficult to be captured and thus exhibited lower dust-suppression efficiency. The above experimental results demonstrated that the dust-suppression efficiency via spraying was highly correlated with the wettability of coal dust. Due to the difference in wetting performance, the dust-suppression efficiency via spraying varied among coal dust particles with different metamorphic degrees. It can also be observed from Figure 13 that the dust-suppression efficiency via spraying was enhanced gradually with the increase of water-supply pressure. Under higher water-supply pressure, smaller droplets moved at a high velocity, and a greater amount of water was atomized in a unit space. As a result, the collision between droplets and dust particle was promoted and the dust-suppression efficiency was enhanced. This conclusion is consistent with the results from theoretical calculation [58, 59, 61, 62].

Table 3 lists the growth rates of dust-suppression efficiency within different pressure ranges. By combining Table 3 and Figure 14, it can be seen that, within the same pressure range, the growth rate of dust-suppression efficiency is different for the 6 coal dust samples. Overall, the coal dust with poor wettability had a larger growth rate, and the difference in the dust-suppression efficiency among 6 coal dust samples gradually decreased with the increase of

Table 2: Atomization characteristics of nozzle under different water supply pressures.

p (MPa)	Q (L/min)	C_v (10^{-6})	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	$D_{[3,\ 2]}$ (μm)	$D_{[4,\ 3]}$ (μm)
0.5	0.50	138.0	103.8	181.5	312.6	145.8	196.8
1.0	1.17	257.2	91.23	150.7	243.3	132.6	159.9
1.5	1.50	333.9	79.47	136.0	225.1	117.6	145.0
2.0	2.00	319.8	67.76	127.9	234.7	106.6	142.1

Note: $D_{[3,\ 2]}$ and $D_{[4,\ 3]}$ refer to the Sauter mean diameter (SMD) and volume-weighted mean diameter, respectively; C_v refers to the volume fraction of the droplet; p refers to the water-supply pressure; and Q refers to the flow rate.

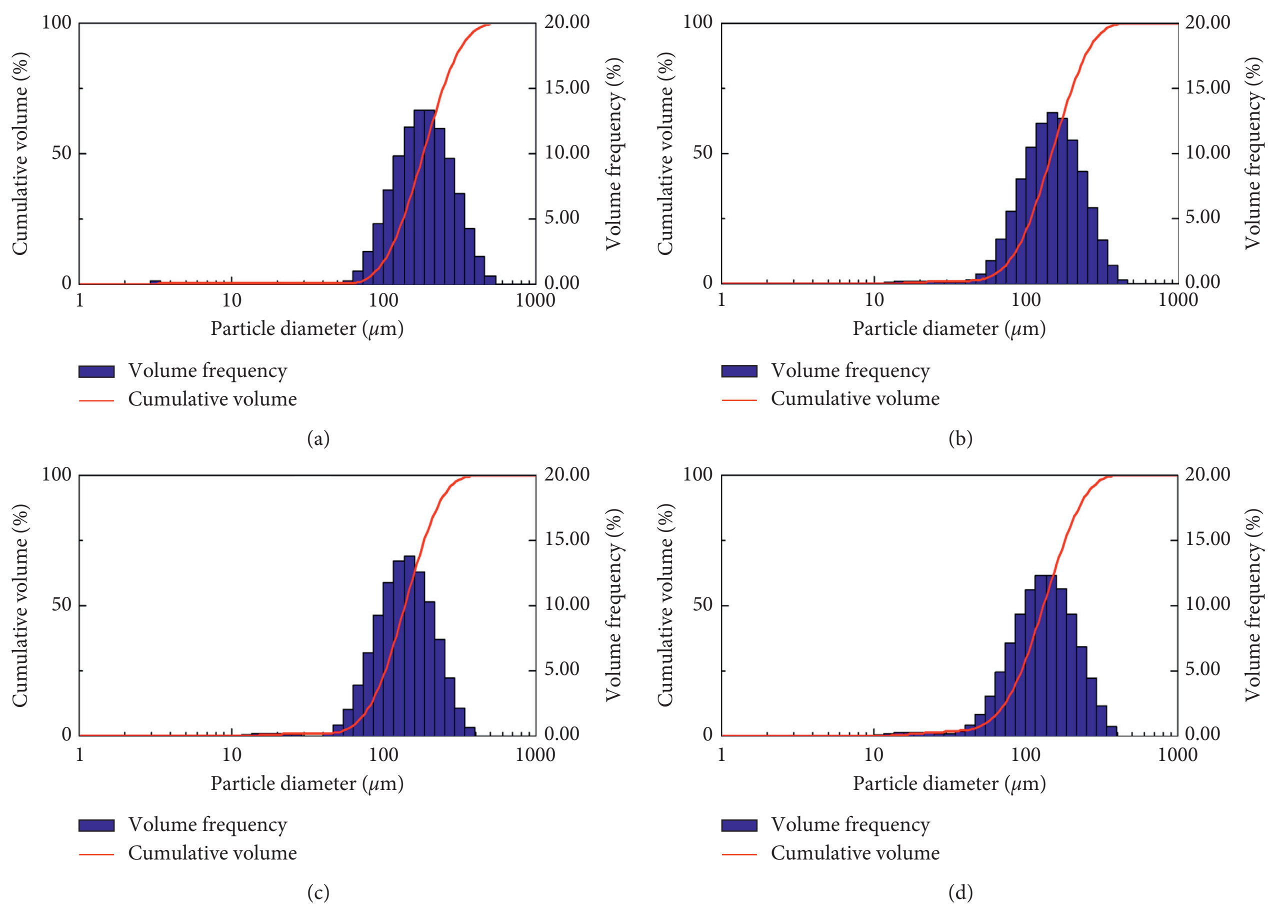

Figure 12: Distribution of droplet size under four different water-supply pressures: (a) $p = 0.5$ MPa; (b) $p = 1.0$ MPa; (c) $p = 1.5$ MPa; (d) $p = 2.0$ MPa.

water-supply pressure. Figure 14 shows the relationship between dust-reduction efficiency via spraying and the contact angle of coal dust. From the figure, when the wettability of coal dust is better, the dust-reduction efficiency is slightly increased with the change of the water-supply pressure. On the other hand, when the wettability of coal dust is poorer, the dust-reduction efficiency is dramatically increased with the change of the water-supply pressure. As water-supply pressure increased from 0.5 MPa to 2.0 MPa, the dust-suppression efficiency was enhanced by only 6.32% for lignite with highest wettability. On the other hand, with the same increase of the water-supply pressure, the dust-suppression efficiency was enhanced by 39.61% and 27.09% for coking coal sample and meager-lean coal with poor wettability, respectively.

When the water-supply pressure was low, the droplet concentration in the roadway space was small, the droplet size was large, and the movement velocity of the droplets was low. As a result, the probability of the collision between the droplet and the dust was low and the bonding ability between them was weak [63, 64]. The dust-suppression efficiency via spraying was related to not only the probability of collision between droplets and dust but also the wettability of coal dust, especially when the water-supply pressure was low. Under low water-supply pressure, the difference in wettability of coal dust can lead to significant difference in dust-suppression efficiency [65, 66]. The dust-suppression efficiency was higher for the coal dust with better wettability and lower for the dust with poor wettability. With the increase of water-supply pressure, the droplet size

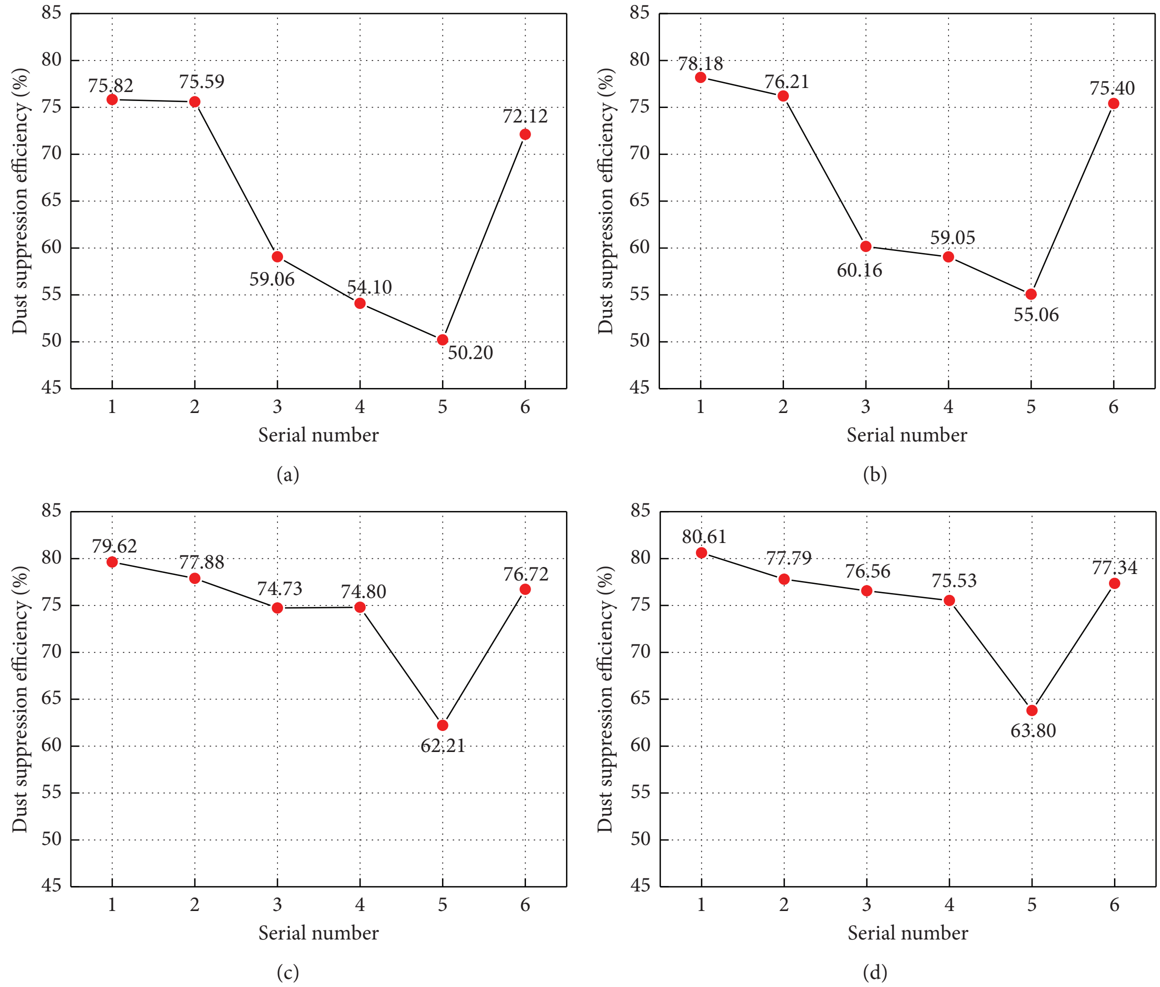

Figure 13: The dust-suppression efficiencies via spraying under different water-supply pressures: (a) $p = 0.5$ MPa; (b) $p = 1.0$ MPa; (c) $p = 1.5$ MPa; (d) $p = 2.0$ MPa.

Table 3: Growth rates of dust-suppression efficiency within different pressure range.

Pressure range (MPa)	Growth rate of dust suppression efficiency (%)					
	Lignite	Gas coal	Fat coal	Coking coal	Meager-lean coal	Anthracite
0.5–1.0	3.11	0.82	1.86	9.15	9.68	4.55
1.0–1.5	1.90	2.21	24.67	29.11	14.24	1.83
1.5–2.0	1.31	−0.12	3.10	1.35	3.17	0.86
Total	6.32	2.91	29.53	39.61	27.09	7.24

continuously decreased, while the concentration and the movement velocity of the droplet were improved. As a result, the probability of collision and bonding ability between the droplet and coal dust were greatly improved. The coal dust with poor wettability had low bonding ability with the droplets. Thus, under low water-supply pressure, the dust-suppression efficiency was low due to the small droplet concentration and low movement velocity. With the increase of water-supply pressure, the droplet concentration and the movement velocity increased significantly, which can reduce the impact of the different wettability of the coal dust [67]. Therefore, the dust-suppression efficiency for the coal dust with poor wettability can be significantly improved with the increase of water supply pressure. The coal dust with good wettability had stronger bonding ability with the droplets and better dust-suppression efficiency under low water-supply pressure. As the water-supply pressure increased, the improvement of the dust-suppression efficiency for the coal dust with high wettability was not as significant as that for the coal dust with poor wettability. Thus, the influence of the wettability of coal dust on dust-suppression efficiency via spraying was reduced with the increase of water-supply pressure. Therefore, with the increase of water-supply pressure, the dust-suppression efficiencies corresponding to the six types of coal dust gradually approached closer, while the gaps among different types of dust were smaller and smaller.

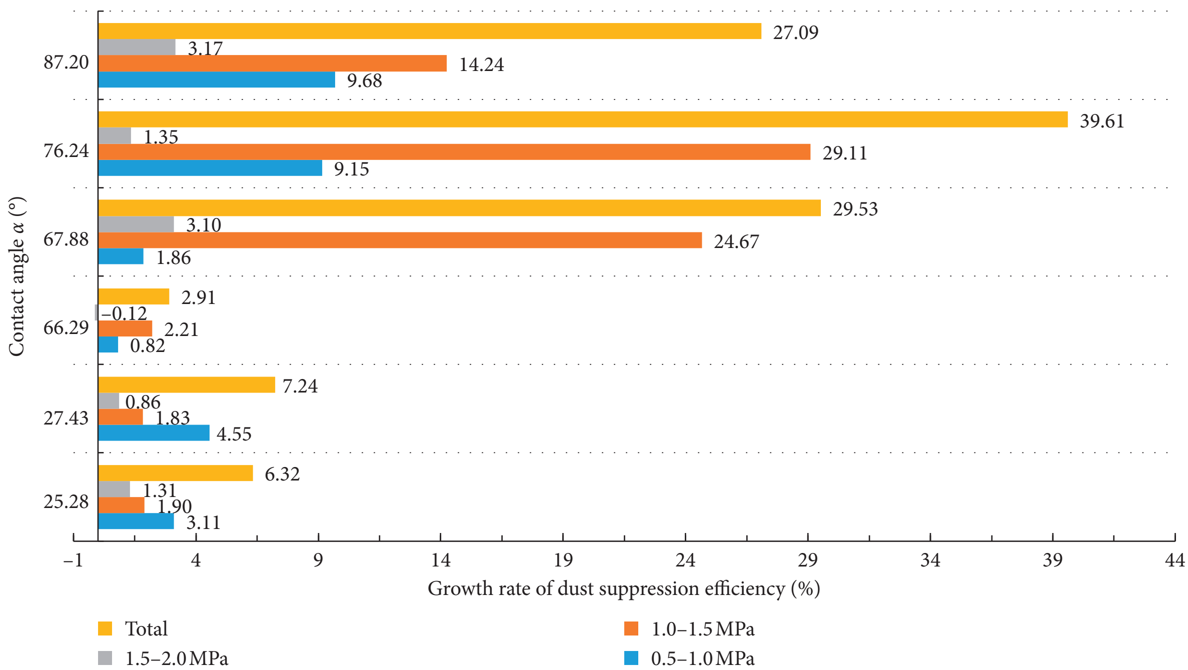

FIGURE 14: Relationship between dust-reduction efficiency via spraying and the contact angle of coal dust.

4. Conclusions

In this study, the microproperties and wetting performances of coal dust with different metamorphic degrees were measured. In addition, the relationship between the wettability of coal dust and the metamorphic degree was investigated, and the influence mechanism of the wettability was analyzed at microlevel. Using the custom-designed experimental platform, the dust-suppression experiment via spraying was performed and the effects of coal dust wettability on the dust-suppression efficiency were obtained. The main conclusions from this study are described as follows:

(1) As the metamorphic degree of coal was improved, the characteristics of the coal dust including the hydrophilic oxygen-containing functional groups on the surface, the surface roughness, the specific surface area, and the internal pore diameter of coal dust all decreased.

(2) As the metamorphic degree of coal was enhanced from lignite to meager-lean coal, the contact angle increased gradually. As the quality of coal was enhanced to anthracite, the contact angle decreased instead of increasing. For all the 5 coal dust samples except anthracite, there was a linear relationship between the content of oxygen-containing functional groups on the surface and the contact angle, and the correlation coefficients of the fitting curve were 0.9394 and 0.8369, respectively. For the coal dust samples with close ash contents, the wettability can be qualitatively and quantitatively evaluated by the areas of the absorption peaks corresponding to oxygen-containing function groups on the surface.

(3) The dust-suppression efficiency via spraying was highly correlated with the wettability of coal dust. The dust-suppression efficiency was higher for the coal dust with better wettability. With the increase of water-supply pressure, the effects of coal dust wettability on the dust-suppression efficiency via spraying decreased, and the difference of the dust-suppression efficiency among different coal dust samples also decreased gradually.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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