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PARTICLES AND FIELDS

Wetting Behavior of Hydrophobic Dust and Dust-Fall Theory of Fine Droplets

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Abstract The wetting behavior of droplets on the surfaces of hydrophobic coal slices is measured with a CCD camera and simulated with the volume of fluid (VOF) numerical method. Experimental results reveal that the contact angle changes exponatially with time and the wettability decreases with the increasing rough microstructures of coal slice surfaces. There is a good agreement between numerical simulations and experimental results. Meanwhile, it is found that droplet with a smaller volume can enhance the hydrophilic. The dust-fall theory of fine droplets is useful to improve the wettability of dust and enlarge the contact ratio between dust and droplets, which can help to design wet-type dust-fall equipment and provide new way for the control of respiratory dust.

Keywords Wetting · Dust · VOF method · Fine droplet

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1 Introduction

Coal, as a main energy source, is widely used in China recently. Meantime, it is a challenge to deal with considerable amounts of dust results from the exploitation of coal resources. Apparently, dust not only does harm to the health of coal workers but also pollutes our environment. So how to control the dust becomes a major concern [1, 2]. At present, water for its dust wetting properties is often used to be a major means to reduce dust. The wetting behavior between droplet and dust determines the dust control efficiency, especially for hydrophobic surface of almost all kinds of coal, which is more difficult to be wetted [3–5].

Wetting is a process of droplet spreading on solid surface. It is reflected by the contact angle (θ), which is used to distinguish hydrophilic and hydrophobic surfaces: hydrophilic ($\theta <$ 90°), hydrophobic (90°$<\theta<$150°), or super-hydrophobic ($\theta >$ 150°) [6]. Yang is the first person who defined the concept of contact angle between water and solid surface

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}, \tag{1}$$

where γ_{LV}, γ_{SV}, and γ_{SL} are separately the specific energies performed liquid–vapor, solid–vapor, and solid–liquid interfaces. A theoretical model that can characterize the wetting behavior proposed by Wenzel (1936) with the increasing solid–liquid contact area is shown in Fig. 1a. The apparent contact angle (θ_W) is expressed by [7]

$$\cos\theta_W = r\cos\theta, \tag{2}$$

where r is the roughness of solid surface, i.e., the ratio between the actual surface area and geometric projection. Another

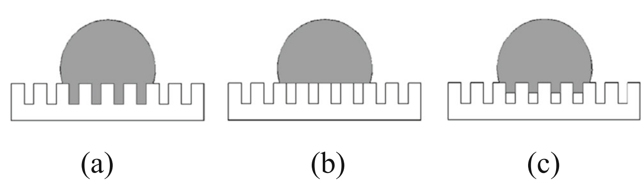

Fig. 1 Sketches of wetting models. **a** Wenzel wetting model; **b** Cassie–Baxter wetting model; **c** Marmur wetting model

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model was given by Cassie and Baxter (1944) to characterize the trapping of air between a droplet and a rough surface, as illustrated in Fig. 1b. The apparent contact angle (θ_{CB}) is expressed by [8]

$$\cos\theta_{CB} = f\cos\theta + f - 1, \tag{3}$$

where f is the area fraction of the solid–liquid interface. In combining Eqs. (2) and (3), it is clear that the microstructure of solid surface has a great influence on their wetting behavior. Sometimes a hydrophobic feature is shown on a hydrophilic solid surface through adjusting the microstructures. Considering a droplet partially wets the surface and partially sits on air pockets, the model has been introduced by Marmur (2003) (Fig. 1c). The apparent Marmur contact angle is given by [9]

$$\cos\theta_M = r_f f\cos\theta + f - 1, \tag{4}$$

where r_f is the roughness of the portion that the solid touches the liquid. When f=1 and r_f=r, Eq. (4) turns into Eq. (2).

Both the interface energies and surface morphologies influence the wetting behavior of droplet on the solid surface. In our work, we investigated the wetting behaviors of coal slices which are made of stacks of dust by experiments and numerical simulations. The results obtained help us understand dust wetting, and several methods are advised to improve the efficiency of dust control [10, 11]. Our studies for the dust wetting are also useful to remove or clean dust and design machines that reduce dust more effectively.

2 Wetting Test

To ensure the coal samples representative, it was collected in accordance with the national standards (GB475-83) strictly. The different dust sizes with D_{50}=208, 152, 84, and 36 μm, respectively, (D_{50} is the volume median diameter of dust distribution) can be obtained by using the jet mill (QLF-120) granularity to process the samples, and the coal dust granularity can be controlled by a particle size analyzer (CIS-100). The coal slice made by applying the compression molding machine (JLO-DJCX) to force the dust under 20 MPa is the cylinder specimens with a length of 13 mm and thickness of 1 mm (Fig. 3a).

The FTA 200 system (First Ten Angstroms, USA) (Fig. 2) was used to capture the droplet spreading process and to record images every 0.1 s under the conditions of room temperature of 20±2° and relative humidity of 55±3 %. The CCD camera in the FTA 200 system has a maximum speed of 30 frames per second. The experimental process (Fig. 3b) and the typical images of a spreading droplet (Fig. 3c) were shown, and the contact angle was measured from the droplet profile using the FTA 200 software. Each experiment was repeated 10 to 20 times on each coal slice, and the experiment was repeated three to five times, and the data obtained were regarded acceptable. For all the rough surfaces, the apparent contact angle was scatted in a range. So we used an average value as the apparent contact angle in the curve-fitting process subsequently.

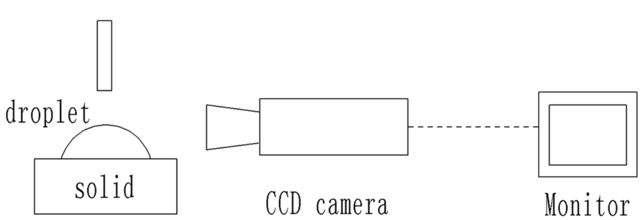


Fig. 2 Sketches of wetting experiment

The wetting results of different coal slices were obtained, as seen in Fig. 4. We could get a great agreement that the contact angle changed exponationally with time, which is consistent with the conclusion mentioned in Ref. [12]. The apparent contact angles were measured to be 81°, 102°, 123°, and 136° in turn for the different coal slices (208, 152, 84, and 36 μm), which suggest that these coal slices are hydrophobic and the wettability decreases with the reducing of D_{50}. The surface of tiny dust has a rougher microstructure which results in poor wettability. The experiment about the influence of surface microstructure on wettability was carried out, and the result obtained is consistent with Ref. [13]. Just as Eqs. (2)–(4) have shown, the wetting behavior of a surface with microstructures under wettability alteration cannot be achieved by the Wenzel and Cassie–Baxter wetting model, but it can be done by the Marmur model.

3 Numerical Simulation

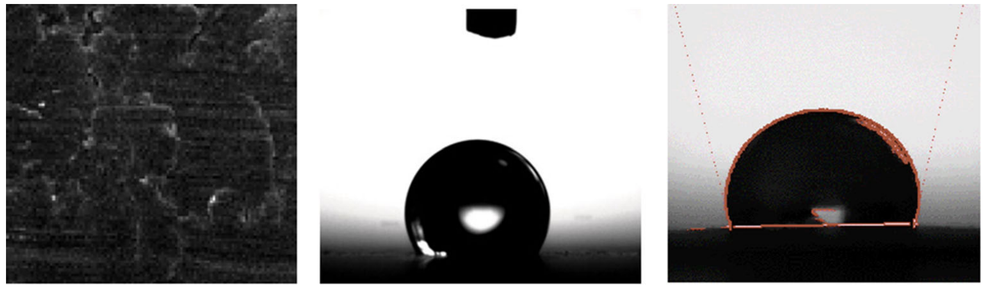
To better understand the effect of microstructure on wettability, a series of numerical simulations was carried out. We consider a two-phase flow approach with a free surface employing volume of fluid (VOF) multiphase model with droplet as the liquid phase and surrounding air as the gas phase. The model is a three-dimensional model which combines a fixed mesh discretization and N–S equations with a piecewise linear volume tracking algorithm to trace the free surface. The droplet is assumed to be an incompressible, viscous fluid. The governing equation can be expressed as [14]

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{5}$$

and the Reynolds time-averaged N–S equation is shown as

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_i} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i + v\frac{\partial^2 u_i}{\partial x_i x_j}, \tag{6}$$

where u_i, i=1, and 2 are the velocity components along the coordinate axes x_i; t is time; ρ, p, and ν are separately the



(a) (b) (c)

Fig. 3 Samples with experimental and wetting process: **a** a coal slice surface with the D_{50} 84 μm; **b** the experimental process; **c** the apparent contact angle with θ 102±1°

liquid density, pressure, and kinematic viscosity; g is the gravity acceleration.

The flow field is computed under unsteady condition without considering the heat transfer and solidification. The liquid droplet is formed by patching the liquid volume fraction with a specified diameter at a low height from the solid surface. The solid surface is considered as the close arrangement of a lot of spheres with equal volume, as shown in Fig. 5.

4 Result Analysis and Dust-Fall Theory of Fine Droplets

A droplet was dropped on the solid surface without vertical speed, and the value of apparent contact angle was obtained through simulation, as shown in Table 1. Compared with the experiment, we found that the value of apparent contact angle by simulation is relatively low. This may be related to the microstructure of the coal surface. We also calculated the apparent contact angles by the Wenze, Cassie–Baxter, and Marmur wetting models and obtained the values of θ as 68°,138°, and 126°, respectively. From Table 1, it is clear that the results by our research agree well with the Marmur wetting model.

The dust is produced from the rock extruded by the cutting tooth; its surface structure changes a large with the effective porosity, specific surface area, and surface free energy increasing [15]. These features are to strengthen the ability of dust particles adsorbing air particles and make its surface form a layer of gas film. The roughness of dust surface enlarges the gas volume trapped in the pore of dust surface and increases the amount of gas film [16]. In fact, the contact process of dust and droplet can be seen as the replacement of the gas film on dust surface by liquid. So it is the gas film that delayed the wetting process and hindered the droplet spreading on dust surface, which can lead to dust hydrophobicity. From the theory of gas film, we can explain that the thinner the dust, the more difficult its surface wets, and that is why the respirable dust is more difficult to be wetted.

In the actual condition of wet-type dustfall, the droplets sprayed from nozzles fell in the space where coal dust floats in the air, contacts with, and sticks on the surface of coal dust. The droplets wrapped by coal dust particles will interact with each other by the attraction through the liquid interface among them, leading to the assembly and aggravation of coal dust.

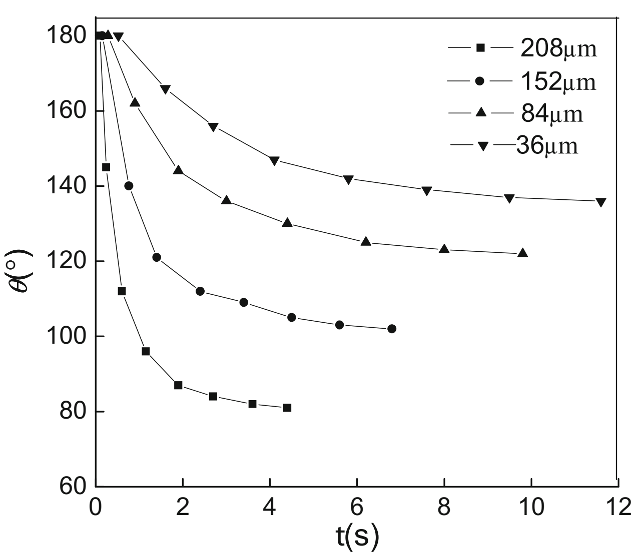


Fig. 4 Change of contact angle by experiment

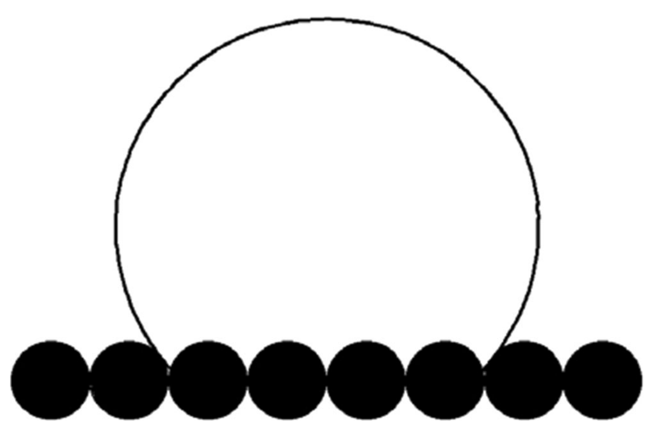


Fig. 5 Simulation wetting model

Table 1 The apparent contact angles under different solid surface

D_{50}/μm	36	84	152	208
Experiment θ/°	81	102	122	136
Simulation θ/°	80	96	114	125

Table 2 The apparent contact angle of different r

r	0.01	0.02	0.05	0.1	0.2	0.5
θ/°	63	69	81	92	98	110

Eventually, when the gravity of this droplet is larger than the flotage, it can fall free, and the assembly of small droplets accelerates the speed [17]. As a matter of fact, the whole surface of droplet is wrapped around by dust particles, and these particles prevent the liquid from contacting with others. So the total surface of droplet becomes a focus to consider further; the research of this not only can enhance the dust-fall efficiency but also save the water.

Based on the above simulation, we carried out a set of numerical simulations about droplets with different volume. The total volume is defined as V_0, and the fine droplet is set as different volume ratio r (0.01, 0.02, 0.05, 0.1, 0.2, and 0.5 V_0, respectively). Each simulation process keeps the total volume of the droplet the same V_0 in order to compare with each other. The wetting process can be divided into three phases generally, as shown in Fig. 6. Firstly, the fine droplets contact with solid surface partly and wet, then others impact on them and the impinging force enhance the wetting of droplet; the fine droplets integrate at last and the apparent contact angle is <90°. Table 2 gives the corresponding contact angle of different volumes of fine droplet under the condition of D_{50} 152 μm, which shows that the fine droplet can improve wettability obviously and the contact angle reduces linearly with the decrease of droplet volume.

From the above analysis, it is found that the total surface area of droplet becomes larger with the increase of r. When a water drop with a volume of V is split into lots of droplets and made each droplet equal volume, the total surface area would be $S_t = \sqrt[3]{36n\pi V^2}$, in which n is the number of all droplets. Therefore, if a water drop is divided into n droplets, the total surface area of a water drop will increase the amount of $\sqrt[3]{n}$ [17]. Thus, to reduce the coal dust more efficiently, a larger surface area should be made by separating a water drop into more smaller droplets, which is consistent with the previous simulation.

The dust-fall theory of fine droplet indicates that the effective surface is the contact area between droplet and dust, and the thinner the droplet is, the more the ratio of effective surface is. The experiment and simulation results agree very well. The collision probability between droplet and dust can enhance with the increase of droplet surface. The secondary dust impacting on the droplet surface may improve the wetting of prior dust; thus, it is assumed that collision frequency contributes significantly to the adhesion between droplets and dust. So the collision probability becomes larger due to the fine spray of droplet. Especially for respiratory dust, the tiny droplet can process multi-field to ensure good contact between dust and droplets by considering the economical use of water. Thus, from the theoretical point of view, the idea of getting fine droplets should be paid more attention in the design of wet-type dust-fall equipment. However, the obtainment of too tiny droplet may increase the burden of the atomizing equipment, for a droplet is too small to fall free due to the gravity, even after integrating with dust. Thus, it is significant to seek for a reasonable scale of droplets according to what we face in the control of dust pollution.

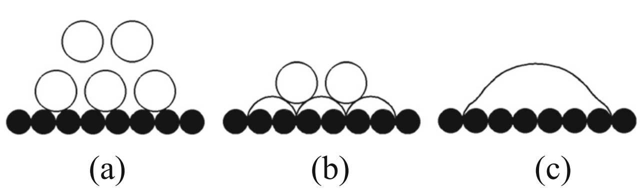


Fig. 6 Simulation results under the fine droplet: **a** the fine droplets contact with solid surface partly; **b** the fine droplets impact on solid surface entirely; **c** the final state

5 Summary

In summary, the wetting properties of droplets on the coal slices formed by different D_{50} have been measured with a CCD camera. Experimental results show that these coal slice surfaces are hydrophobic and the wettability decreases with the reducing D_{50} and the contact angle changes exponatially with time. We simulated the wetting process of droplet on different coal slices by using VOF numerical method. For the same droplet, the complex microstructure of solid surface can improve the hydrophobic, which is in agreement with the experimental results; for the same solid surface, the tiny volume of droplet can enhance the hydrophilic.

Both experimental and simulation results indicate that the effective contact surface between droplet and dust contributes to the total dust-fall, that is, the fine droplet can not only enlarge the ratio of effective surface but also change the wettability of dust. The dust-fall theory of fine droplet can also help us to design wet-type dust-fall equipment and provide new ideas for the management of respiratory dust.

References

1. Y.Q. Li, Y.P. Qin, X.B. Yang, L. Tian, New progress on coal mine dust in recent ten years. Procedia Eng. **26**, 738–743 (2011)
2. E. Ilknur, A. Hamit, D. Vedat, U. Suphi, Pneumoconiosis and quartz content of respirable dusts in the coal mines in Zonguldak, Turkey. Int. J. Coal Geol. **116**(117), 26–35 (2010)
3. Q.Z. Li, B.Q. Lin, S. Zhao, H.M. Dai, Surface physical properties and its effects on the wetting behaviors of respirable coal mine dust. Powder Technol. **233**, 137–145 (2013)
4. C.M. Neuman, J.W. Boulton, S. Sanderson, Wind tunnel simulation of environmental controls on fugitive dust emissions from mine tailings. Atmos. Environ. **43**(3), 520–529 (2009)
5. H.J. Annegarn, A.D. Surridge, H.S.P. Hlapolosa, D.J.D.V. Swanepoei, A.R. Horne, A review of 10 years of environmental dust monitoring at Crown Mines. J. Mine Vent. Soc. S. Afr. **44**(3), 46 (1991)
6. S.M. Gowder, J. Chatterjee, T. Chaudhuri, K. Paul, Prediction and analysis of surface hydrophobic residues in tertiary structure of proteins. Sci. World J. **2014**, Article ID 971258, 7, (2014).
7. R.N. Wenzel, Resistance of solid surfaces to wetting by water. Ind. Eng. Chem. **28**(8), 988–994 (1936)
8. A.B.D. Cassie, S. Baxter, Wettability of porous surfaces. Trans. Faraday Soc. **40**, 546–551 (1944)
9. A. Marmur, Wetting on hydrophobic rough surfaces: to be heterogeneous or not to be? Langmuir **19**(20), 8343–8348 (2003)
10. Q.Z. Liu, Z.M. Kou, Z.N. Han, G.J. Gao, Dynamic process simulation of droplet spreading on solid surface by lattic boltzmann method. Acta Phys. Sin. **62**, 234701 (2013)
11. O. Oguntoke, M.E. Ojelede, H.J. Annegarn, Frequency of mine dust episodes and the influence of meteorological parameters on the Witwatersrand Area, South Africa. Int. J. Atmos. Sci. **2013**, Article ID 128463, 10 (2013).
12. Y.F. Gao, D.Y. Sun, Molecular-dynamics simulations of droplets on a solid surface. Chin. Phys. lett. **27**(6), 066802 (2010)
13. F.F. Bi, Y.L. Guo, S.Q. Shen, J.X. Chen, Experimental study of spread characteristics of droplet impacting solid surface. Acta Phys. Sin. **61**, 184702 (2012)
14. N. Othman, S.K. Kamarudin, M.S. Takriff, M.I. Rosli, E.M.F. Engku Chik, M.A.K. Adnan, Optimization of a continuous hybrid impeller mixer via computational fluid dynamics. Sci. World J. **2014**, Article ID 619474, 6 (2014).
15. C.P. Please, D.P. Mason, C.M. Khalique, Fracturing of an Euler-Bernoulli beam in coal mine pillar extraction. Int. J. Rock Mech. Min. Sci. **64**, 132–138 (2013)
16. J. Yang, X.K. Wu, J.G. Gao, G.P. Li, Surface characteristics and wetting mechanism of respirable coal dust. Min. Sci. Technol. **20**, 0365–0371 (2010)
17. Y. Yu, Q. Wu, X.W. Wang, X.B. Yang, Wetting behavior between droplets and dust. Chin. Phys. Lett. **29**(2), 026802 (2012)