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EFFECT OF MOISTURE CONTENT IN COAL DUST ON FILTRATION AND CLEANING PERFORMANCE OF FILTERS

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Abstract: A large amount of fugitive coal dust is generated during the mining, transportation, and processing of coal. The moisture content of the coal dust has a significant influence on the dust collection performance of filters, although relatively few studies on this phenomenon exist. This study deals with six groups of coal dust samples with moisture contents ranging from 0 to 12 wt.% and tested the pressure drop as the coal dust was deposited onto three different types of filters. The specific resistance, compression coefficient, and porosity of the coal dust cake were analyzed, and the cake/filter adhesive force was tested using the reverse flow cleaning method. This research demonstrates that the influence of the moisture content on the specific resistance, compression coefficient, and porosity of the coal dust cake can be divided into two phases (according to the critical moisture content of 4 wt.%): first, as the moisture content increased from 0 to 4 wt.%, the cake resistance and compression coefficient increased and the cake porosity decreased; and second, as the moisture content increased from 4 to 12 wt.%, the cake resistance and compression coefficient decreased and the porosity increased. The coated and repellent filters possessed a lower adhesive force on the coal dust cake than the conventional filter. The comparison of all three of the filters revealed that the adhesive force between the repellent filter and the dust cake was the least sensitive to the moisture content.

Keywords: coal dust, moisture content, filtration, compressibility, adhesive force

Introduction

Throughout the mining, transportation, and processing of coal, a large amount of fugitive coal dust is inevitably generated. Human exposure to coal dust results in pneumoconiosis with an initiation and progression of pulmonary fibrosis. Other dangers associated with coal dust include serious explosion hazard and quite severe

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environmental pollution (Demir and Kursun, 2012; Finkelman et al., 2002; Ozbayoglu, 2013). Filter-type collection is commonly utilized for coal dust control and possesses a high collection efficiency, especially for fine dust (Cecala et al., 2012, Li et al., 2015).

Moisture exists in coal at various levels that change constantly during its transportation and processing. The moisture content influences the physical properties of the coal dust particles and thereby influences the dust collector performance factors, such as the filtration pressure drop and the filter regeneration efficiency. Under particularly high dust concentration conditions, water spraying is typically conducted along with the filter-type collection methods, which increases the moisture content of the coal dust and significantly influences the effectiveness of the dust filtration.

Previous studies have mostly focused on the influence of the particle size, shape, and/or chemical composition during the filtration and cleaning processes (Choi et al., 2002; Park et al., 2007; Salazar-Banda et al., 2012). The previous findings generally agree that the filtration pressure drop increases and dust cake porosity decreases with a decrease in the particle size (Kim et al., 2008; Lupion et al., 2014) and that the more irregular particles tend to form a higher pressure drop and are more compressible (Choi et al., 2002). The effects of the chemical composition on the filter cake strength and adhesion were much more varied, and these have also been studied at length (Lupion et al., 2014; Salazar-Banda et al., 2012). Few studies have investigated the effect of the dust moisture content on the filter performance (Joubert et al., 2010).

It should be noted that many researchers have studied the influence of air humidity on the clogging and cleaning performance of flat filters (Gupta et al., 1993; Joubert et al., 2010; Joubert et al., 2011; Park et al., 2007). The air humidity changes the increasing rate of the pressure drop, alters the particulate deposition pattern, and changes the particle-to-particle adhesive force. To a certain extent, air humidity also affects the moisture content in the dust and vice versa. Because coal is a hydrophobic material, it is not readily deliquesced by capillary condensation in humid air. The primary deliquescent mechanism in coal is molecular diffusion, which requires a lengthy amount of time as moisture diffuses from open air into the pores of dust particulates. Furthermore, air humidity mainly affects the filtration air flow and the surface properties of the dust. The moisture content may be more likely to affect the density of the dust than its surface properties.

This paper focuses on the influence of the coal dust moisture content on the filtration and cleaning performance of filters. Six groups of coal dust samples with moisture contents ranging from 0 to 12 wt.% were prepared, and the filtration pressure drop during coal dust deposition was measured on three types of filters. The specific resistance, compression coefficient, and porosity of the coal dust cake were analyzed. The adhesive force between the dust cake and the filter was also studied utilizing the reverse flow cleaning method.

Theory

Gas filtration

During the filtration of dust-laden air, particulates are captured and deposited onto the filter. A dust cake forms on the surface of the filter, and this cake traps most of the particulates within it. In general, the total filter pressure drop (ΔP_T) can be considered the sum of the pressure drop in the filter medium (ΔP_F) and the pressure drop across the dust cake (ΔP_C), as expressed in Eq. (1) (Chen et al., 2012; Cheng and Tsai, 1998):

$$\Delta P_T = \Delta P_F + \Delta P_C = k_1 v_f + k_2 v_f W \tag{1}$$

where k_1 is the resistance of the filter (Pa·s/m), k_2 is the specific resistance of the cake (1/s), v_f is the face velocity of filtration (m/s), and W is the dust mass deposited per unit area (kg/m^2).

The filter drag (S) represents the value of the pressure drop across the dust cake and is expressed as follows:

$$S = \Delta P_C / v_f = k_2 W \tag{2}$$

where the specific resistance k_2 can be expressed by the following equation (Cheng and Tsai, 1998; Choi et al., 2002):

$$k_2 = f v_f^n \tag{3}$$

where f and n are constants and n indicates the dust cake compressibility in terms of the filtration velocity.

The dust cake specific resistance k_2 has a relation to the porosity ε and can be expressed as (Choi et al., 2002; Neiva et al., 1999):

$$k_2 = 180(1-\varepsilon)\varepsilon^{-3}(\rho_P \varphi_s{}^2 d_s)^{-1}\mu \tag{4}$$

where ε is the cake porosity, ρ_P is the true density of the dust (g/cm^3), d_s is the Sauter mean particle size (μm), ϕ_s is the particle sphericity and μ is the viscosity of air (kg/(s·m)). The specific resistance k_2 is determined based on the pressure drop test data and the calculations according to Eq. (2); once the specific resistance has been determined, the cake porosity ε can be calculated according to Eq. (4).

In general, the mass of the dust loading onto the filter is a function of the variable filtration pressure drop (Choi et al., 2002; Joubert et al., 2010). However, the density of a dust particulate distinctly changes with a change in the moisture content, rendering it not appropriate to employ mass loading as the variable when studying the influence of moisture content in dust as a function of the drop in the filter pressure. To this effect, the dust's true volume deposited per unit area was utilized as the filtration variable in this study. Equations (1) and (2) were rewritten accordingly and are expressed as follows:

$$\Delta P_T = \Delta P_F + \Delta P_C = k_1 v_f + k_2^{'} v_f V \tag{5}$$

$$S = \Delta P_C / v_f = k_2^{'} V \tag{6}$$

where V $(=W / \rho_P)$ is the dust true volume deposited per unit area (m^3/m^2), $k_2^{'}$ is the specific resistance of the cake in the true volume mode ($Pa{\cdot}s/m^2$), and $k_2^{'}$ can be expressed by the equation $k_2^{'} = f^{'} V_f^n$, where $f^{'}$ is a constant. Additionally, $k_2^{'} = k_2 \rho_P$ and $f^{'} = f \rho_P$.

Adhesive force

As far as reverse flow cleaning, a method suggested by Seville et al. (1989) has proven appropriate for the estimation of the cake/filter adhesive force by observing a flow of gas in the direction opposite to that of filtration. The cake behaves similarly as in the filtration cycle when the cleaning air flow is below the critical removal velocity. Rupture occurs in the cake/filter surface as the critical velocity is reached. The pressure drop through the filter and cake can be written as

$$\Delta P_{Tc} = k_1 v_c + \Delta P_{Cc} \tag{7}$$

where ΔP_{Tc} is the pressure drop on the cleaning (Pa), v_c is the face velocity of the cleaning gas (m/s), and ΔP_{Cc} is the pressure drop in the cake (Pa). Under these conditions, ΔP_{Cc} represents the cake/filter adhesive force per unit area.

The Seville method is widely used to determine the adhesive force and provides satisfactory results (Salazar-Banda et al., 2012; Tanabe et al., 2011).

Experimental

Equipment set-up and procedure

A diagram of the experimental set-up is shown in Fig. 1. The equipment consisted of a dust feeder, test chamber, pressure drop recorder, air flow meter, and exhaust fan. The test filter was installed perpendicularly to the direction of the air flow in the filtration chamber and possessed a total filtration area of 78.5 cm^2. The air flow face velocity in the chamber could be tuned to 1.5 – 8.8 cm/s by adjusting the regulation valve.

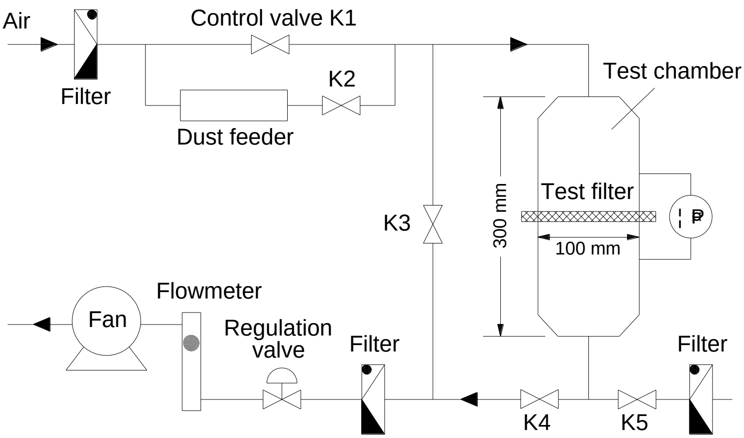

Fig. 1. Sketch of the experimental set-up

The values of the pressure drop during the dust clogging and reverse flow cleaning were recorded using this experimental set-up. The room temperature was maintained at 9–15 °C, and the air humidity was maintained between 50 and 65% during each test period. In the filtration mode, four filtration velocity levels, i.e., 3.50, 4.24, 4.97 and 5.28 cm/s, were selected for the test. First, the control valves K1 and K2 were opened, and the rest were closed. Next, the fan was started. And the flow velocity was adjusted to the desired value using the regulation valve. Dust was then added into the feeder (hard operations were performed in the isovolumetric adding mode, and the dust was added 15 times for each clogging period in the isogravimetric mode in increments of 0.1 ± 0.005 g). Dust was entrained by the air flow when the K2 valve was opened and the K1 valve was closed. The dust-laden air was then flowed into the test chamber, and the air flow was switched from valve K2 to valve K1. The desired filtration velocity was maintained for 30 s to obtain a stable dust cake, and the pressure drop was then recorded. Subsequent dust additions were conducted utilizing the same method.

After dust addition was performed 15 times, the experimental system was switched to the reverse flow cleaning mode for the adhesive force testing. First, the control valves K1, K2, and K4 were closed, and the K3 and K5 valves were opened. The removal velocity was increased incrementally from 1.5 to 2.6, 3.5, 4.4, 5.3, 6.2, and 7.1 cm/s. The pressure drop during cleaning was recorded after a duration of 30 s at each step.

Test filters

Three filters were selected for testing. The first filter was a conventional filter, which is a non-woven long staple polyester medium with a thermo-bonded surface – this type of medium is one of the most extensively used in the industry and is favored for its small pressure drop and reasonable price. The second filter was a coated filter, which is a non-woven polyester medium coated with a fine polytetrafluoroethylene (PTFE) membrane. For a surface treatment with microporous layers, this type of medium provides highly effective filtration. The third filter was a repellent filter, a non-woven polyester medium with a water-repellent treatment. Scanning electron microscope (SEM) views of the filter media are shown in Fig. 2, and the filter properties are presented in Table 1.

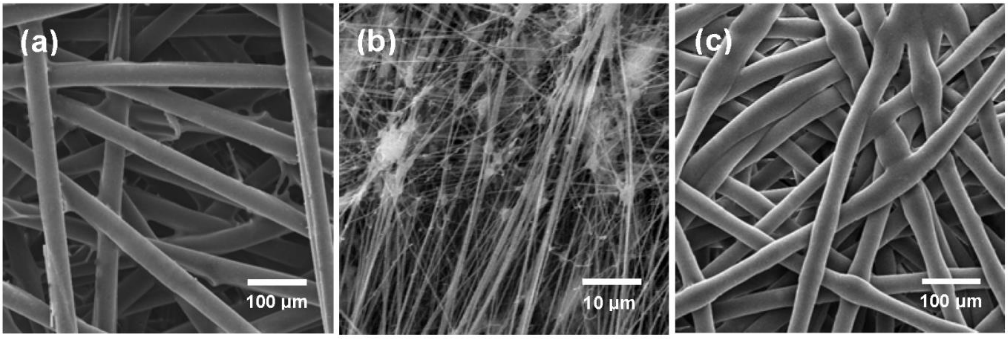

Fig. 2. SEM views of the surface of the (a) conventional, (b) coated, and (c) repellent filter media

Table 1. Filter properties

Parameters	Conventional filter	Coated filter	Repellent filter
Surface treatment	Thermo-bonding	Microporous coating	Water repellent
Surface mass (g/m^2)	240 ± 3	255 ± 5	260 ± 5
Thickness (mm)	0.50 ± 0.05	0.62 ± 0.05	0.55 ± 0.05
Fiber diameter*(μm)	18.41 ± 1.5	0.19 ± 0.20	19.82 ± 3.0
Resistance (Pa·s/cm)	8.91	42.57	19.93

*Calculated from the 20 fibers shown in the SEM images

Coal dust

In this research, coal dust with a diameter of less than 75 μm (the typical particle size of fugitive coal dust,) was collected after the jet coal sample from the Yuejin Coal Mine (Yima City, Henan Province, China) was crushed and ground. The coal dust sample was first dried at 110 °C for 3 h to remove the total moisture, according to the procedure established by the Chinese National Standard the Determination of Total Moisture (GB/T 211-2007). The sample was then divided into six groups, five of which were sprayed with different amounts of water to obtain coal dust samples with moisture contents of 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.% and 12 wt.%. The moist dust samples were sealed and stored for a month to ensure a uniform distribution of moisture in the dust particulates. The moisture content values of each dust sample were tested before the filtration testing, and the relative biases were less than 3%. Particle size distributions were obtained using a Microtrac S3500 Particle Size Analyzer in the dry measurement mode (Table 2). The particle size was not notably affected by a moisture content between 0 and 12 wt.%. The repose angles of the dust were also measured using a BT-1000 Powder Integrative Characteristics Tester.

Table 2. Properties of the coal dust

M (wt.%)	ρ_P (g/cm^3)	d_{50} (μm)	d_s (μm)	φ_s (-)	Repose angle (°)
0	1.394	34.92	29.86	0.782	36.8
2	1.470	35.33	29.84	0.778	41.7
4	1.443	35.76	30.05	0.779	47.6
6	1.461	35.78	30.06	0.782	50.4
8	1.478	36.06	30.11	0.808	54.1
12	1.532	36.37	30.16	0.811	59.9

Results and discussion

Effect on filtration pressure drop

Figure 3 shows where the filtration pressure drops changed with the dust load and moisture content for the conventional filter. The pressure drop increased with the dust load. During the clogging process of a clean filter, this increase in pressure drop generally exhibited three stages (Mao et al., 2008), which is described as follows. Stage I is characterized by an accelerating increase in the rate of the pressure drop. Stage II is characterized by a decelerating increase. Stage III is characterized by a constant increase. Stage I provides mostly deep filtration where dust particulates deposit inside the filter. Stage II acts as a transition from deep to surface filtration where some particulates deposit inside and some deposit onto the surface of the filter. Stage III is the surface filtration stage in which the first dust layer has formed on the surface of the filter and subsequent particulates are captured by this layer. All three stages were clearly observable during our tests, as can been observed in Fig. 3 and in accordance with previous reports (Mao et al., 2006; Mao et al., 2008). The pressure drop values increased with similar tendencies for differing moisture contents.

A comparison of the filtration pressure drop curves for different moisture contents demonstrated that the overall pressure drop increased as the moisture content increased from 0 to 4 wt.%. For the moisture content in the range of 4 to 12 wt.%, the pressure drop decreased as the moisture content increased. To further investigate the pressure drop as it changed with changes in the moisture content, the pressure drop values were extracted under a loaded dust true volume V =10×10^{-5} m^3/m^2 for the conventional, coated, and repellent filter conditions (Fig. 4). The pressure drop for the conventional, coated, and repellent filters showed similar variation tendencies – first an increase and then a subsequent decrease with increasing moisture content – with a maximum pressure drop value at M = 4 wt.%. The differences in the filtration pressure drop between these three filters were mainly attributable to the resistance of each filter itself.

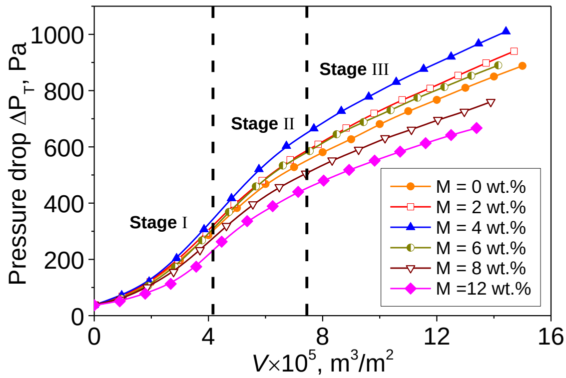

Fig. 3. Filtration pressure drop of a loaded conventional filter as a function of moisture content in coal dust (M = moisture content)

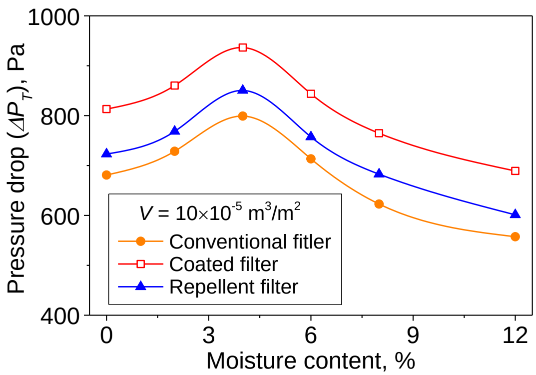

Fig. 4. Filtration pressure drop as a function of the moisture content when a loaded dust true volume $V = 10 \times 10^{-5}$ m^3/m^2 was utilized for the conventional, coated, and repellent filters

Effect on dust cake

S-V curves showing the effects of the face velocities in the range of 3.50 to 5.28 cm/s and the moisture contents in the range of 0 to 12 wt.% for the conventional filter are shown in Fig. 5. As can be found in Fig. 5, the increase in the filter drag (S) with a dust load (V) in Stage I and Stage II was not linear. It means that the dust cake compressibility (n) was not constant with the dust load according to the equations $S = \Delta P_C / v_f = k_2' V$ and $k_2' = f' V_f^n$. This is because, in Stage I and Stage II, most or some of the dust particulates deposited inside of the filter rather than be captured by the dust layer, which has a complex influence on the formation of the dust cake.

However, in stage III, almost all of the dust particulates deposited on the dust layer and a constant value of the dust cake compressibility was obtained. Therefore, Stage III of the filtration test was the focus for a clear comparison of the dust cake compressibility for the different moisture contents and filtration velocities. The results of the calculated $k_2^{'}$ are shown in Fig. 6a.

For the same moisture content, the cake specific resistance $k_2^{'}$ increased with the filtration velocity; for the same filtration velocity, $k_2^{'}$ first increased and then decreased as the moisture content increased, with the maximum at 4 wt.%.

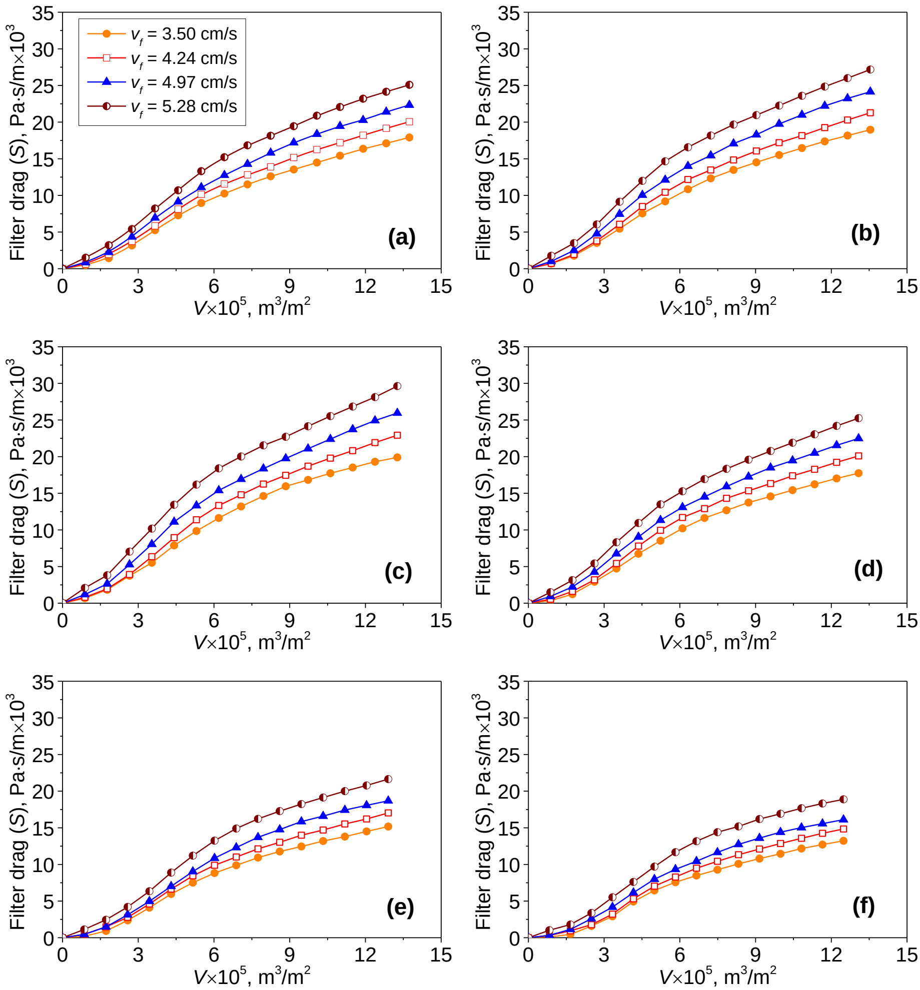

Fig. 5. *S-V* curves showing the effects of the face velocities for the conventional filter: (a) moisture content = 0 wt.%, (b) 2 wt.%, (c) 4 wt.%, (d) 6 wt.%, (e) 8 wt.%, and (f) 12 wt.%

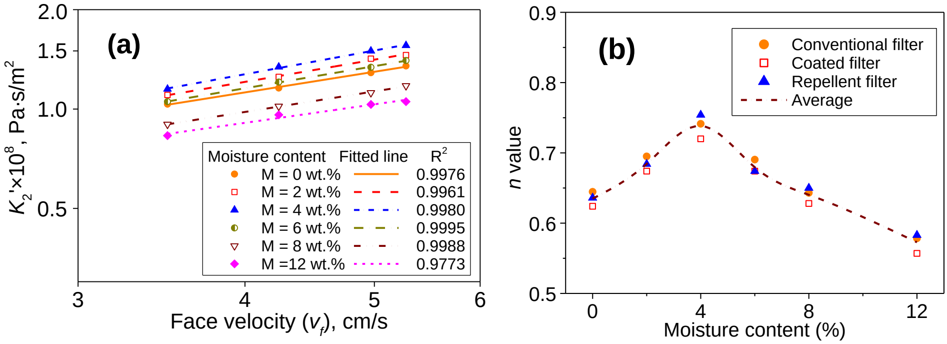

Fig. 6. Correlation curves of (a) the specific resistance $k_2^{'}$ as a function of the face velocity , and (b) the compression coefficient *n*, which was obtained from the relationship between $k_2^{'}$ and v_f , as a function of moisture content

Based upon the changes in the $k_2^{'}$ value, which corresponded with the filtration velocity, as well as the known relationship $k_2^{'} = f^{'} v_f^n$, the values of the compression coefficient *n* were determined through curve fitting, as shown in Fig. 6a. In the same manner, the values of the compression coefficient *n* on the coated and repellent filter conditions were obtained, as shown in Fig. 6b. The compression coefficient *n* was stable in all three filter conditions. The average *n* values were 0.635, 0.684, 0.738, 0.679, 0.640, and 0.573 for moisture contents M = 0 %, 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.%, 12 wt.%, respectively, demonstrating that the compression coefficient first increased and then decreased with a corresponding increase in the moisture content, with a maximum at 4 wt.%.

The values of the cake porosity ε were also calculated using Eq. (4) (μ =1.8×10^{-5} kg·s^{-1}·m^{-1}), as shown in Fig. 7. The cake porosity ε first decreased and then increased with a corresponding increase in the moisture content, and its minimum was obtained at a moisture content of 4 wt.%.

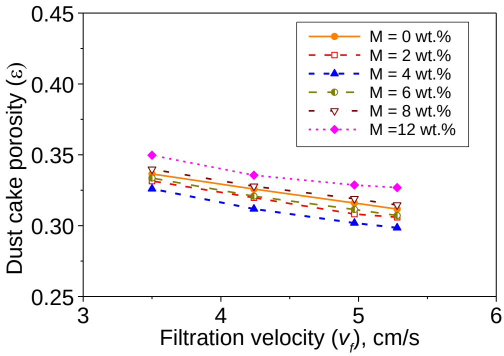

Fig. 7. Correlation curves of porosity ε with moisture content

Previous researchers (Joubert et al., 2010; 2011) have studied the effects of air humidity on the filtration pressure drop and have found that the pressure drop and dust cake porosity decreased monotonously with an increase in the air humidity. They posited that the particle-to-particle adhesive force increased with increasing relative humidity, where depositing particles were less effectively squeezed and a more open cake was formed, lowering the pressure drop for a given amount of particulate loading. This finding suggests that the effects of the dust moisture content and the air humidity on the filtration performance should be different. To better understand this difference, it is necessary to analyze the forces which act upon the dust particles during filtration.

During dust filtration, once a particle makes contact with the surface of a previously deposited particle, it is subject to mainly compression forces (including wind force Fw and inertial force Fi,) and resistant forces (mainly including a friction force F_f, adhesive force F_a, and a braced force F_b) from the deposited particle. The contribution of gravity is considered negligible for the small particles in this study. It was also assumed that particles do not bounce upon colliding.

The relationship between these forces is detailed in Fig. 8. The friction force was calculated by $F_f = \beta \cdot [F_a + (F_w + F_i) \cdot \cos\theta]$, where β is the friction coefficient of the two contacting particles with values usually between 0 and 1, and θ is the angle between the line connecting the centers of the two contacting particles and the vertical line with values between 0° and 90°. The compression force can be divided into a normal force and a shear force. When the shear compression force is larger than the friction force, the particle will slide down, i.e., the forces meet the following discriminant:

$$(F_w + F_i) \cdot \sin\theta] > \beta \cdot [F_a + (F_w + F_i) \cdot \cos\theta] \tag{8}$$

Otherwise, the particle will not move.

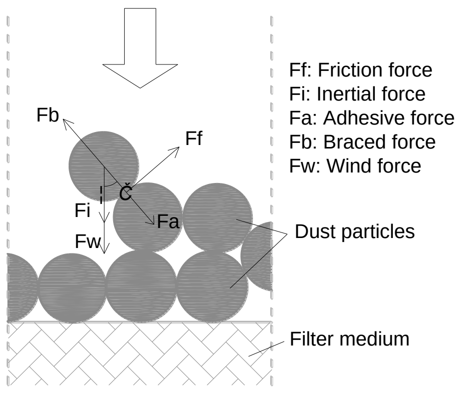

Fig. 8. Relationship between the forces acting on a particle in a dust cake

Under the conditions set by Eq. 8, the value range of θ decreases with an increasing adhesive force F_a and a friction coefficient β. In the statistical sense, this suggests that fewer particles can slide down and the dust cake compressibility decreases. At the same time, the value range of θ increases with an increase in the compression force ($F_w + F_i$), and this causes more particles to slide down and the cake compressibility to increase.

An increase in the moisture content primarily increases the particle density, the friction coefficient (reflected by the repose angle shown in Table 2, where a higher repose angle means a greater friction coefficient,) and the surface adhesiveness (Joubert et al., 2010), which consequently increases the inertial force F_i, friction force F_f, and the adhesive force F_a as well. Under the same filtration velocity conditions, the wind force F_w can be considered the same due to the similar particle sizes of the coal dust with different moisture contents (Table 2). It is easy to assume that in relatively low moisture content conditions, the dust particle surface friction coefficient and adhesiveness do not increase as dramatically as the density and that a sharper increase in the inertial force over the friction/adhesive forces renders the dust cake more compressed. With a moisture content between 4 and 12 wt.%, the dust particle surface friction coefficient and the adhesiveness increases more obviously than the density, forming a more open cake. This suggests that as the moisture content increases from 0 to 4 wt.% the dust cake structure is more compact, and as moisture content increases from 4 wt.% to 12 wt.%, the cake structure tends to be loose. Fig. 9 depicts this phenomenon between the dust particles (simplified as spheres with a uniform size with a moisture content of 0 %, 4 wt.%, and 12 wt.%).

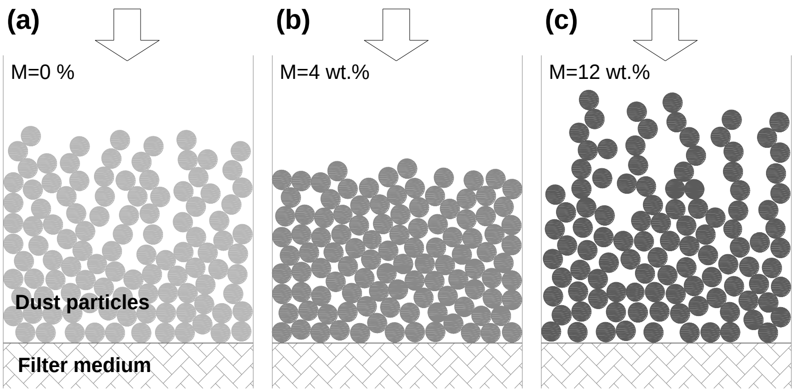

Fig. 9. Deposition morphology of the coal dust cake

Compared to the moisture content, the effect of air humidity on the dust focuses mostly on the particle surface. As the air humidity increases, the friction and adhesive forces increase more than the inertial force, causing the degree of cake compression to increase monotonously. To this effect, the differences between the influences on the dust filtration performance between the moisture content in the dust and air humidity are most likely caused by discrepancies in the particle density, surface friction, and particle-to-particle adhesive force.

Effect on cake/filter adhesive force

Figure 10a shows the pressure drop across the conventional filter as a function of the cleaning velocity where the filtration velocity was v_f = 4.24 cm/s. The pressure drop values that corresponded with the conditions of moisture content M = 0 % and 2 wt.% with a velocity of v_c = 1.5 cm/s and M = 4 wt.%, 6 wt.%, 8 wt.%, and 12 wt.% with v_c = 1.5 and 2.6 cm/s did not match the fitted line of the pressure drop values corresponding to the same moisture content conditions with higher velocities (unfitted data in Fig. 10a). The unmatched values corresponded to non-ruptured dust cakes on the filter; in other words, the corresponding velocities were under the critical removal velocity. The adhesive force can be calculated after the rupture occurs on the cake/filter surface, according to Eq. (7). For the conventional filter, the values of the cake/filter adhesive force per unit area ΔP_{Cc} were 143.59, 147.13, 152.87, 163.85, 175.06, and 218.52 Pa for moisture contents of 0%, 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.%, and 12 wt.%, respectively. The cake/filter adhesive force was obtained in the same manner for the coated and repellent filters.

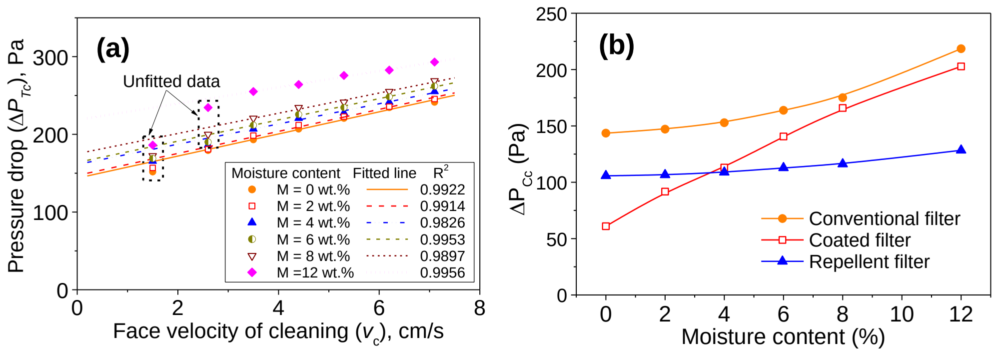

Fig. 10. Pressure drop upon cleaning where the filtration face velocity v_f = 4.24 cm/s: (a) total pressure drop as a function of the cleaning face velocity, obtained using conventional filter, and (b) pressure drop in the cake as a function of the moisture content for the conventional, coated, and repellent filters

The cake/filter adhesive forces for the three filters are shown in Fig. 10b. The cake/filter adhesive forces increased with an increase in the moisture content in the range of 0–12 wt.% for all three filters, and the adhesive forces for the coated and repellent filters were lower than for the conventional filter. For a moisture content between 0–4 wt.%, the coated filter possessed the lowest adhesive force with the coal dust cake, while for a moisture content between 4 wt.% and 12 wt.%, the repellent filter possessed the lowest.

The adhesive force increased by 1.52 times for a conventional filter when the moisture content increased from 0 to 12 wt.%, 2.90 times for the coated filter, and 1.21 times for the repellent filter – basically, for all three filters, the adhesive force was the most sensitive to the moisture content between the dust cake and the coated filter and the most insensitive between the cake and the repellent filter.

Conclusions

1. The filtration pressure drop ΔP, cake specific resistance $k_2^{'}$, and compression coefficient n first increased and then decreased with an increase in the moisture content in the coal dust, and maximum values were observed with a moisture content M = 4 wt.%. In contrast, the cake porosity ε first decreased and then increased, also reaching a maximum value at M = 4 wt.%.
2. The moisture content of the dust showed notable differences from the air humidity in terms of influencing the dust cake resistance, compressibility, and porosity, and this could be attributed to the discrepant changes in the particle density, surface friction, and particle-to-particle adhesive force.
3. The adhesive force between the coal dust cake and conventional filter was larger than the force between the cake and the coated or repellent filter for moisture contents M between 0 and 12 wt.%. At M = 0–4 wt.%, however, the lowest adhesive force was found between the coal dust and the coated filter, and for M = 4–12 wt.%, the repellant filter presented the lowest adhesive force. The adhesive force was observed to be most sensitive to the moisture content between the dust cake and the coated filter and least sensitive to the moisture content between the cake and the repellent filter.

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