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An investigation of the effect of particle size on the flow behavior of pulverized coal

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Abstract

In this paper, pulverized coal from industry was used as the experimental material and sieved into seven samples with different particle size. The effect of particle size on the flow properties of pulverized coal was investigated. An annular shear cell was used to measure angle of internal friction, angle of effective internal friction, cohesion and angle of wall friction, and a transparent Perspex hopper was used to determine the discharge characteristics of pulverized coal. The experimental results showed a significant effect of particles size on the cohesive and angle of wall friction rather than on the angle of internal friction. Jenike's procedure was used to predicate the flow pattern of pulverized coal with different particle size, which linked with the discharge experiment. Three regions including arching, unstable-flow and mass-flow were obtained based on the analysis of weighting curves and a progressive transition from blocking to unstable flow and to mass flow was observed as the particle size increased. In addition, the failure properties of pulverized coal was investigated which supported the region division. The investigation showed that the effect of particle size on the flow properties of pulverized coal is diversity and rheological test results can reflect flow properties of pulverized coal to some extent.

Selection and peer-review under responsibility of Chinese Society of Particuology, Institute of Process Engineering, Chinese Academy of Sciences (CAS)

Keywords: pulverized coal; rheology; flow properties; hopper discharge

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1. Introduction

Entrained-flow pressurized gasification process of pulverized coal, including the storage, discharge and conveying of pulverized coals, is one of the best contemporary coal gasification technologies[1,2]. Handling and storage of pulverized coal are known to produce well-known problems like bridging, channeling, fluctuating flow rate or even blocking in process equipment and storage as the tendency of agglomeration causing by the strong interaction between the particles. All of these problems have significant effects on the continuous, stable, and long-period operation of the gasifer. Thus, the trouble-free treatment of pulverized coals presents large problems as well as scientific and technological challenges.

Prescott and Barnum stated[3] that since the flowability is not an inherent property of a material, but instead results from a combination of physical property and environmental factors, it cannot be described by any one value or single index. There are many factors influence the flowabiilty of powders, the physical properties, e.g. particle size, particle size distribution, particle shape, specific surface area, surface morphology and environmental factors e.g. consolidation, absorbed gas, and relative humidity.

A number of both experimental and theoretical studies of the flow properties of powders have been carried out over the past few years. Juliano[4] studied the bulk and flow properties of salt, sugar , cocoa and cheese and other commercial powders. Cohesive powders tend to have bigger angle of response, unconfined yield stress and cohesion than non-cohesives while their frictional characteristics are basically close. Fu[5] evaluated the flow and bulk properties of three lactose powders differ in particle shape or size, indicating that besides the particle size, the shape of the particles would also significantly influence the flow properties of the particles , which demonstrated that improving the shape of the lactose can efficiently enhance flow properties. Carnavas[6] quantify the shape of copper particles using two–dimensional images and correlated the shape factors with powder flow and packing properties, which showed that powders comprised of particles with greater deviation from spherically have lower flow rates, lower packing densities and higher interparticle friction. The effect of particle shape on velocity, volume fraction, granular temperature and stress distribution across the channel in simple shear flow is quantitatively explored by DEM simulation[7]. Particle shape is found to sharply increase the strength of material and the flow of non-circular particles leads to high granular temperatures, dilative pressures and lower solid fractions in the core of the flow. The surface composition of industrial spray-dried food powders were estimated by ESCA(electron spectroscopy for chemical analysis) and correlated with the flow properties of the powders[8], which demonstrated that the surface composition affect the food powders flowability significant and the presence of free-fat will causing poor flowability.

Fitzpatrick[9] evaluated the effect of chemical composition , temperature, relative humidity on the flow properties of milk powders by shear test. Iqbal[10] evaluated the effect of storage conditions(temperature, relative humidity, storage time)on wall friction characteristics and hopper design for flour, tea and whey permeate powders using the shear testing technique of the Jenike shear cell.It is found that wall friction increased with temperature foe flour and tea powders while it decreased for whey permeate powder and the increase of relative humidity resulted in an increase in wall friction and hopper angle requirement. Landi[11] studied the effect of air humidity on flow properties of fine glass beads by means of shear tests and established a model based on the Kelvin equation and the Laplace-Young equation, which can describe the condensation between touching particles and to estimate the relevant interparticle forces.

Some of the researchers tried to compare results of different flowability-test methods for the purpose of optimizing flowability representation. Guerin[12] tested the voidage of medical powders by means of mercury porosimetry and studied the compressibility and flowability of medical powders using vibration and shear tests. Through analyzing the followed results, Guerin evaluated and discussed suitable applied categories for different testing measurements. Vasilenko[13] evaluated the effect of flow additives and active pharmaceutical ingredients on the bulk and flow properties of powders by three different flowability-testing methods, including Gravitational displacement rheometer, compressibility test and shear test, and evaluated the relationship among the relevant tested parameters. Chevannan[14] fabricated a direct shear cell to measure the flow properties of chopped switch grass, wheat straw, and corn stover to given useful information for the development of efficient handing, storage, and transportation systems for biomass .

Following the background above, It can be seen that most investigations on powder flow properties are mainly focused on the area of medicine and food, but there is death information on the flow properties of pulverized coal. Therefore, the objectives of this paper are(a) to determine the effect of particle size on flow properties of pulverized coals by testing the cohesion, internal friction angle and unconfined yield stress of pulverized coals.(b)to apply Jenike methodology to calculate the hopper design parameters of the pulverized coals to predict the discharge behaviors and verify the prediction by discharge test.

Nomenclature

d_v	mean volume diameter, μm
D	particle size, μm
De	mean particle size, μm
τ	shear stress ,Pa
σ	normal stress, Pa
φ	angle of internal friction, deg
C	Cohesive, Pa
φ_e	effective angle of internal friction, deg
σ_1	major principle stress, Pa
σ_c	unconfined yield stress, Pa
CBD	conditioned bulk density, g/ml
ρ_p	particle density, kg/m^3
A	Hamaker constant, J
ff_c	flow index
ff	flow factor
g	acceleration due to gravity, m
M	relative flow rate

2. Material and methods

2.1. Materials

The initial materials for this study are industrial bituminous pulverized coal having a particle density of 1490 kg/m3.The initial materials sieved into seven samples with different particle size. The characteristics of the samples obtained after screening are reported in Table 1.

Table 1. Physical properties of all coal materials. All particle size data in this is a volume average.

Material	$d_{0.1}$(μm)	$d_{0.5}$(μm)	$d_{0.9}$(μm)	d_v(μm)	n
a	15.69	169.90	518.27	223.80	0.91
b	14.48	115.46	309.37	141.30	1.02
c	12.52	86.44	186.56	94.20	1.11
d	11.09	68.94	146.93	74.90	1.12
e	9.85	50.94	108.85	55.95	1.21
f	9.50	39.51	81.76	43.24	1.30
g	4.31	15.02	35.47	17.70	1.20

The particle size distribution of the pulverized coal in the experimental can be described using the Rosin-Rambler distribution function[15,16].The general expression of the Rosin-Rambler is:

$$R(D) = 1 - \exp[-(\frac{D}{D_e})^n] \quad (1)$$

where $R(D)$ is the distribution function, and D is the particle size ,De is the mean particle size and n is a measure of the spread of particle size, increasing n will decreasing the size range. As shown in Table 1, the samples have roughly the same level of size range , which means it is the particle diameter that mainly influence the experimental results.

2.2. Methods

2.2.1Shear cell and wall friction test

Fig. 1. Image of the shear cell supplied with the FT4 powder Rheometer (a) measuring powder flow functions; (b)measuring angle of wall friction

An rotational shear tester was used to quantify the incipient flow behaviors of experimental materials , which consists of a vessel containing the samples and a shear head to introduce both vertical and rotational stresses, as shown in Fig 1(a).

A conditional cycle should first be done before formally tests, which using the standard FT4 blade in order to remove any residual compaction and build a uniform and loose condition in the bed of powders. Then a vented piston is used to induce a precise consolidation stress in the sample. After that, the vessel is split and shear cell head is used to reconsolidate the sample to ensure that the surface of the sample is suitably consolidated. When the previous works were done, the shearing sequence is started. Base on the normal and shear stress collected , the yield locus at a given pre-consolidation can be acquired by linear regression using the Mohr-Coulomb equation:

$$\tau = \sigma \tan \varphi + C \quad (2)$$

Where, τ is the shear stress(kPa), σ is the normal stress(kPa), φ is the angle of internal friction, C is the cohesion(kPa).

The wall friction test is similar to the shear test, which replace the shear head by a Perspex plate , of the same material quality with the hopper, as shown in Fig 1(b). It is typical to measure a series of shear stress values for a range of reducing normal stress to generate a wall yield locus, from which the angle of wall friction is determined.

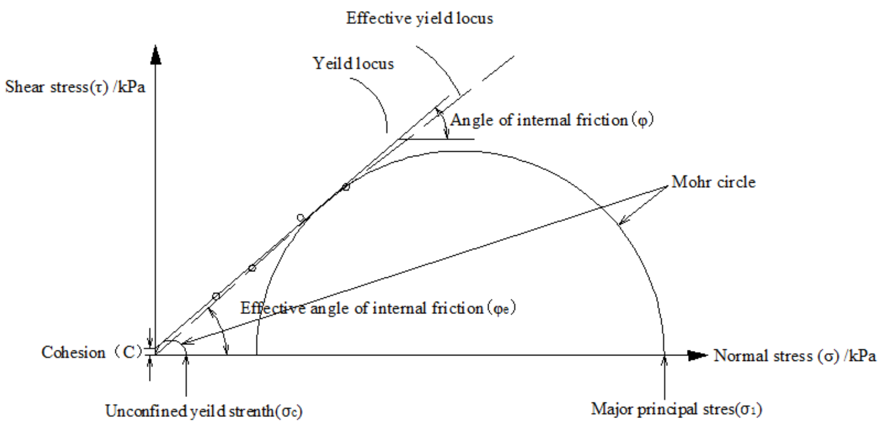

Fig. 2. Mohr circles, yield locus and effective yield locus

Fig 2 is typical σ-τ diagram, showing two Mohr circles, yield locus, and effective yield locus. Base on these terms, the angle of internal friction φ, effective angle of internal friction φe , cohesive C, major principle stress σ1, and unconfined yield stress σc can be calculated.

2.2.2Hopper discharge

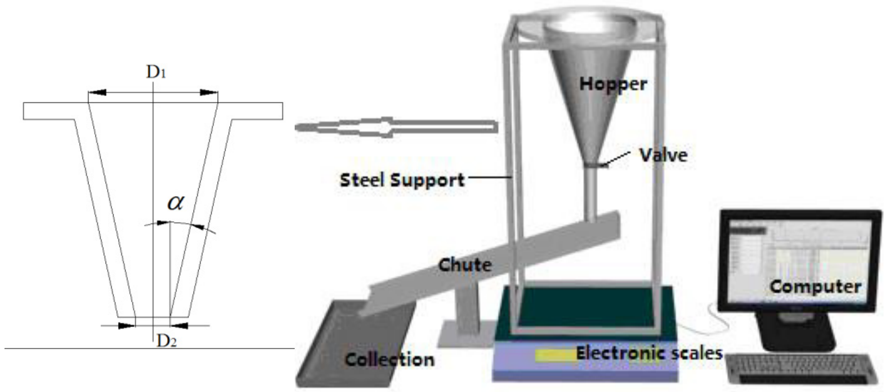

Fig. 3. Schematic of the hopper

To dynamically and directly observe flow properties of coal powders in the hopper, a transparent Perspex hopper was fabricated to determine the flow behavior of the pulverized coals with mass flow rate in advance . As shown in Fig 3, the hopper of 15° in half angle, 150 mm and 32 mm in top and bottom diameter, respectively. In each case, a sample of 0.7 kg was loading in the hopper and the sample was loosely packed. Discharge immediately after loading to avoid consolidation caused by long residence time and the relationships between mass and time was determined and recorded by a hanging weighing unit to acquire discharge weighing curve.

3. Results and discussion

3.1The results of shear cell and wall friction

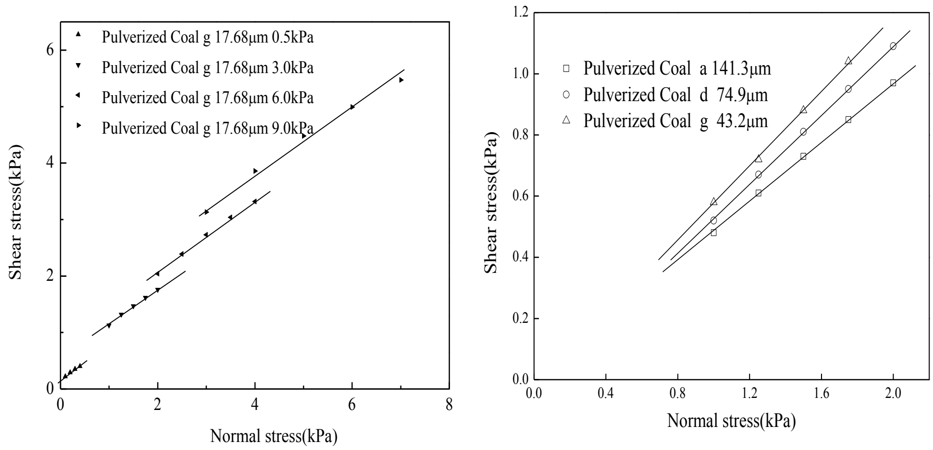

Fig. 4. (a) The yield locus under different degree consolidation of coal g (b) Experimental wall shear stress

Fig 4(a) displayed the yield locus under different degree consolidation of coal g. Fig 4(b) shown a typical wall frictional test result. The shear and wall frictional characteristics reflected the ability of the powders to flow over themselves and the inner surface of hopper, respectively.

3.1.1Conditional bulk density

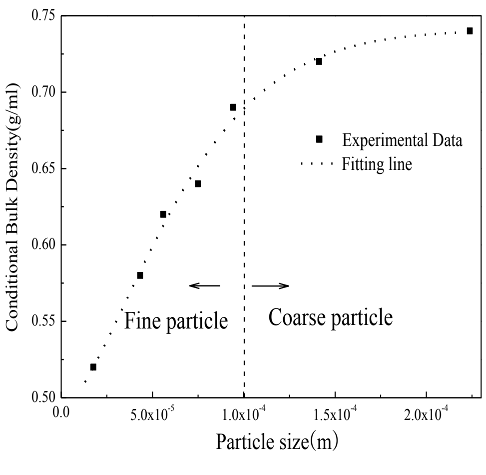

Fig. 5. Conditioned Bulk Density as a function of particle size

The conditioned bulk density of the pulverized coals in terms of their dependence on particle size is plotted in Fig.5. The *CBD* (conditioned bulk density) represents the bulk density that the material would have if the condition cycle is done. A low stress, homogeneous packing state is established after the conditioned cycles, which can reflect the packing efficiency of the samples. In this study , a model equation describing the relationship between the packing density(or voidage) of powders and the particle size was applied[17]:

$$CBD = CBD_{\infty} - CBD_{\infty} \exp[-0.237(\frac{\rho_p}{A})^{0.0836} d_v^{0.273}] \tag{3}$$

Where, ρ_p is the particle density, kg/m^3.A is the Hamaker constant. For graphite, A is equal to 3.47×10^{-19}J, which may be used for pulverized coal as an approximation. And d_v is the equivalent volume diameter of the pulverized coals. $CBD_{\infty}$is the bulk density without any interparticle force and corresponds to the packing of coarse particles where gravity is the only dominant force. For this study, CBD_{∞} is equal to 0.9551g/ml。

For dry powders study here, the van der waals forces are the dominant interparticle forces, so the competition between interparticle and gravitational forces significantly influences the packing efficiency of the pulverized coals. The experimental result demonstrates that the conditioned bulk density decrease with the decrease in particle size as the van der waals forces restricts the relative motion between particles in forming a packing. However once particle size is larger than a critical value, around 100μm, the *CBD* is not such sensitive to particle size. Therefore, two size regions can be identified in this research: one is referred to as fine region in which the packing efficiency varies significantly due to the effect of van der waals forces, and the other coarse region in which the packing efficiency not significant varies with particle size as the gravity is dominant. Consequently,100μm is believed to be the critical diameter, on basis of which coarse particles and fine particles are divided. In the following sections, the effect of particle size on both fine and coarse particles are compared discussed.

3.1.2Angle of internal friction and cohesion

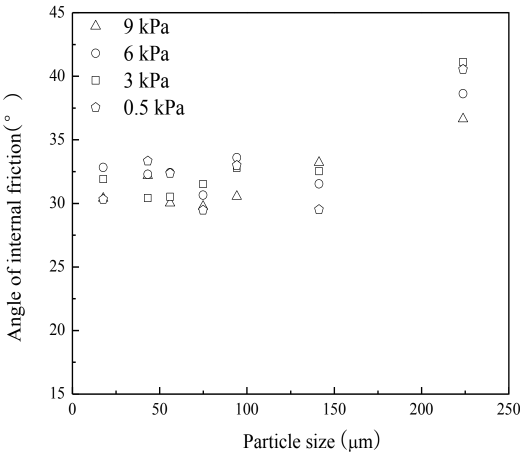

Fig. 6. Effect of particle size on the angle of internal friction under different degree of consolidation

Fig 6 shows the relationship between the angle of internal friction and particle size under different consolidation stress. It is evident that the angle of internal friction not sensitive to particle size or consolidation stress ,but the internal friction angle of 223.8μm pulverized coal is transparent larger than that of other samples.

There are two major factors causing the internal friction: one is interlocking and the other intrinsic value of friction between particles [4].For 223.8μm pulverized coal, the affect of interlocking is more significant as the relative large particle size and hence gives a high angle of internal friction. For the other pulverized coals, the surface characteristics are similar and the effect of intrinsic value of friction between particles is more significant that interlocking; as a consequence, the angle of internal friction not varied with the particle size.

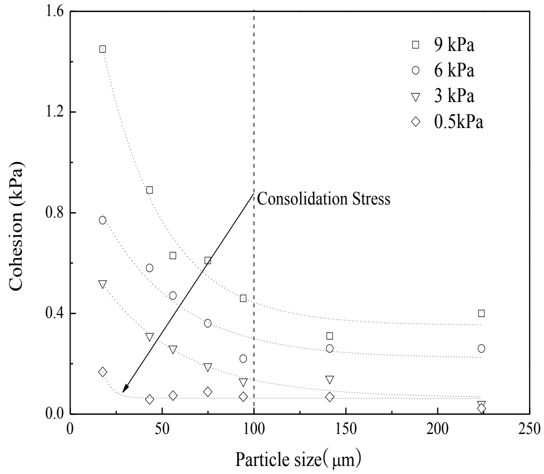

Fig. 7. Effect of particle size on the cohesion under different degree of consolidation

Fig 7 shows the relationship between cohesive and particles of the pulverized coals at different pre-consolidation stress states. It can be seen for a given consolidation stress , the cohesive increase significantly with the decrease of the particle size in fine particle region and the higher the consolidation stress is, the more significant the trend is. In contrast, the cohesive no longer sensitive to the particle size in the coarse particle region. In addition, the cohesive increase with the increase of consolidation stress ,especially for fine particles.

As shown in these results ,there are significant changes of failure properties of pulverized coal with the changes of particle sizes and consolidation stress. The effects of the particle size and consolidation stress on the angle of internal friction are less significant than the cohesive. Furthermore, pulverized coals in fine particle region are more sensitive to consolidation.

3.1.3Classification of the flowability of the pulverized coals

The ratio between the major consolidation stress σ_1 and the unconfined yield stress is the so-called flow index, $ff_c=\sigma_1/\sigma_c$.Base on the flow index, the powder materials are classified as hardened, very cohesive, cohesive , easy flowing , or free flowing[18] , as shown in Table 2.

Table 2 Jenike(1964)classification of powder flowability by flow index

	Flow index				
	*ff*c<1	1<*ff*c<2	2<*ff*c<4	4<*ff*c<10	*ff*c>10
Flowability	Hardened	Very cohesive	Cohesive	Easy flowing	Free flowing

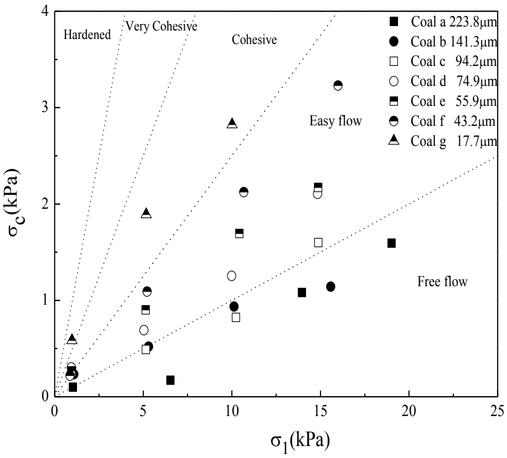

Fig. 8. Flow functions of the pulverized coals

Fig 8 shows the flow functions as the inverse of flow index for pulverized coals. According to the Jenike classification given in Table 2, the flow index values decrease counter-clockwise from the region of free flow to Hardened, as shown in Fig 8. Flow function measurements for the pulverized coals shows that 223.8μm, 141.3μm pulverized coals belong to the free flow region, 94.2μm belong to boundary of free flow region and easy flow region, 55.59μm and 43.2μm belong to the easy flow region , while 17.7μm belong to the cohesive region.

The result shown that, the flowability of pulverized coal increased with the increase of particle size. According to Jenike classification, the pulverized coals in coarse particle region belong to free flow powders and the pulverized coals in fine particle region belong to easy flow or cohesive powders. According to Kokova[19] , only sample powders keep the same flowability in different stress regions. Therefore, the pulverized coals are complex powder whose flow behavior may result in different when the consolidation stress is changed.

3.1.4The angle of wall frictional

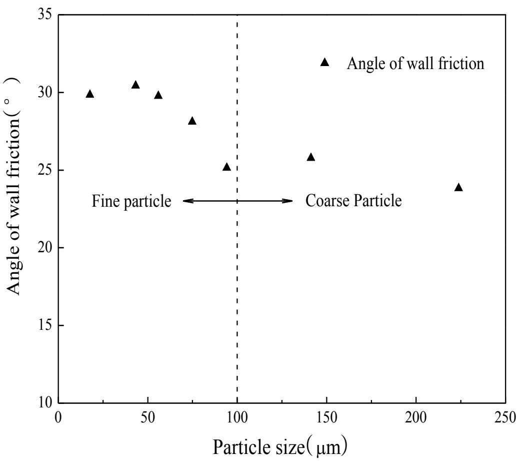

Fig. 9. Effect of particle size on the Angle of wall friction

Wall friction measurements were conducted for the pulverized coals. The relationship between angles of wall friction and particle size of pulverized coals is presented in Fig 9 . It is clear that the relationship between angle of wall friction and particle size are different in coarse particle region and fine particle region.

Within the range of coarse particles (>100μm), the angle of wall friction of the pulverized coals is relatively small and independent of the particle size. In contrast, in fine particle region, the angle of wall friction will increased significantly with the decrease of particle size, which indicate that the action between wall and particle will be a mainly effect on the flow behavior of pulverized coals.

3.2Prediction of flow behaviors

Base on the shear and wall friction properties of materials, Jenike applied two-dimensional stress analysis to develop a numerical methodology to determine minimum hopper angle and hopper opening size for mass flow discharging from conical and wedge shaped hoppers. This method was partly applied to semi-quantitative predict the effect of particle size on the discharge behaviour of pulverized coals. Fig 10 illustrated the stress state of the outlet of hopper.

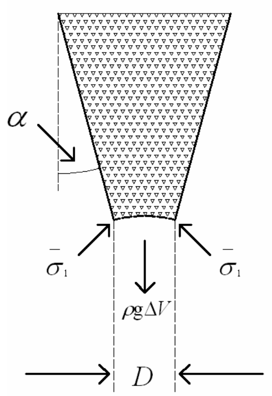

Fig. 10. Stress state of outlet

In Jenike method, the hopper half angle(α) can be calculated from angle of wall friction(φ_w) and the effective angle of internal friction(φ_e) using the following equations:

$$\alpha = \frac{\pi}{2} - \frac{1}{2}\cos^{-1}\frac{(1-\sin\varphi_e)}{2\sin\varphi_e} - \beta \quad (4)$$

Where

$$\beta = \frac{1}{2}\left\{\varphi_w + \sin^{-1}\frac{\sin\varphi_w}{\sin\varphi_e}\right\} \quad (5)$$

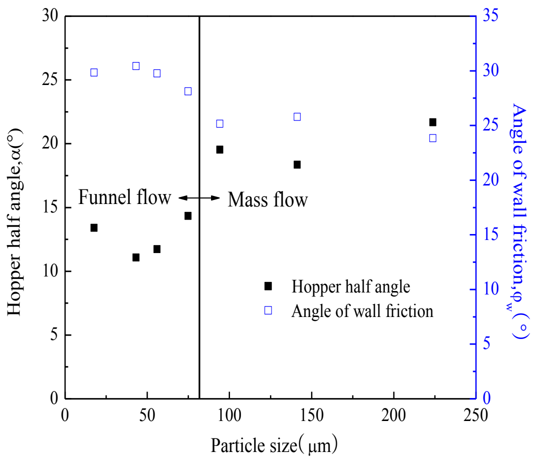

Fig. 11. Hopper half angle as a function of particle size

Fig 11 given the effect of particle size on the calculated hopper half angle of the pulverized coals. Compare to wall friction results, we can found that the interaction between wall and pulverized coals have a significant effect on the design of maximum hopper half angle. Within the fine particle regions, in order to achieve mass flow a steeper slope is needed as the significant increase of interaction between the wall and pulverized coals.

Meanwhile, Jenike concluded, with the flow-no flow criterion, that a stable cohesive arch will form in a convergent channel when the unconfined yield strength σ_c exceeds the major stress in the local arch above the outlet of the channel, $\bar{\sigma}$. When $\bar{\sigma} > \sigma_c$,a forming arch will collapse, that is, the critical point is the condition $\bar{\sigma} = \sigma_c$.

Therefore, the value of critical stress can be acquired from the plot of the flow function *FF* against the flow factor *ff* which is defined as $ff = \sigma_1 / \bar{\sigma}$ to described the capability of the hopper walls to discharge a solid under gravity,.

The flow factor (*ff*) is a function of the effective angle internal friction(φ_e), the hopper half angle(α) ,and the wall friction(φ_w). The flow factor is calculated from the following equations:

$$ff = \frac{Y(1+\sin\varphi_e)H(\alpha)}{2(X-1)\sin\alpha} \tag{6}$$

Where

$$X = \frac{2\sin\varphi_e}{1-\sin\varphi_e}[\frac{\sin(2\beta+\alpha)}{\sin\alpha}+1] \tag{7}$$

$$Y = \frac{[2(1-\cos(\beta+\alpha))]\cdot\sin\alpha+\sin\beta\cdot\sin^2(\beta+\alpha)}{(1-\sin\varphi_e)\cdot\sin^3(\beta+\alpha)} \tag{8}$$

$$H(\alpha) = [\frac{130+\alpha}{65}] \tag{9}$$

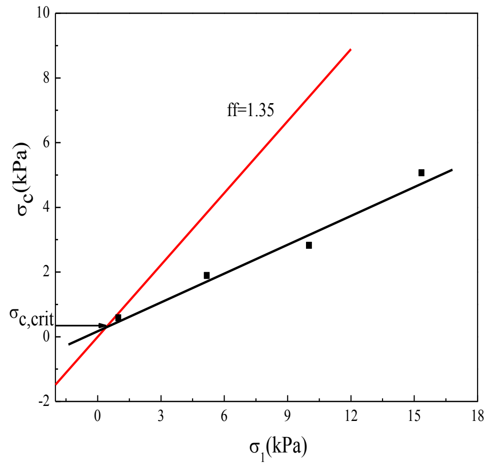

Fig. 12. Diagram showing properties of coal f for the determination of CAS(critical applied stress)

As an example, Fig 12 shows the determination of critical applied stress of coal f with the particle size 43.2μm. The critical applied stress for the pulverized coal is found from the intersection of the flow function curve and flow factor line, which is, the straight line passing through the origin and have a slope of 1/*ff*. When the flow factor line is above the flow function curve, correspond to $\bar{\sigma} > \sigma_c$, then a flow will happen, and vice versa. Thus, at the intersection point we can get $\bar{\sigma} = \sigma_c$, the stress in the arch at the boundary of the "flow/no flow" condition , which the critical applied stress $\sigma_{c,cri}$ is given.

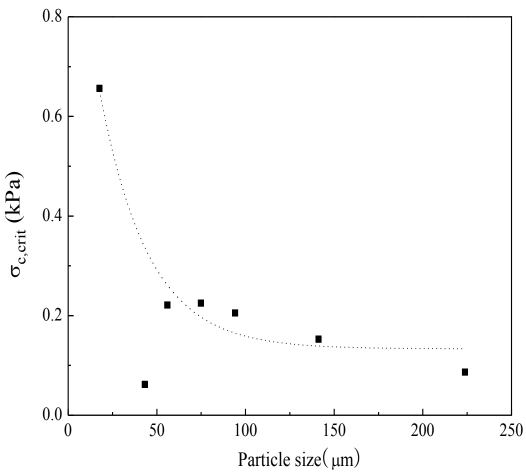

Fig. 13. Critical applied stress as a function of particle size

Fig 13 shows the relationship between critical applied stress and particle size for the pulverized coals .As the particle size decreases, an upward tendency of critical applied stress is performed for the pulverized coals. Also, we found that the coal f with the particle size 43.2μm, which has an extreme small critical applied value than expected. The flow function curve of coal ,f, is very steep, and when linearly extrapolated, result in a low unconfined yield stress axis intercept, which leads to the relatively low critical applied stress value. A similar conclusion was observed in previous research by Fitzpatrick et al[20] and pan Chen[21].

Table 3 Calculated values of critical applied stress and the maximum hopper half angle for the pulverized coals.

Material	d_v(μm)	*CBD*(g/ml)	*ff*	α(°)	$\sigma_{c,crit}$(kPa)
a	223.8	0.74	1.57	21.68	0.087
b	141.3	0.72	1.7	18.34	0.155
c	94.2	0.69	1.68	19.53	0.208
d	74.9	0.64	1.54	14.33	0.224
e	55.95	0.62	1.49	11.74	0.218
f	43.24	0.59	1.48	11.08	0.061
g	17.7	0.52	1.35	13.41	0.656

The calculated values of hopper half angle and critical applied stress for the pulverized coals are shown in table 3. With the particle size of pulverized coal increases, the maximum hopper half angle and critical applied stress of pulverized coal are increased, especially in fine particle region. Decreasing particle size of pulverized coal will lead to the increase of cohesive and angle of wall friction, causing flow problem over itself and inner surface of the hopper, respectively, thus causing harsh hopper design parameters. For the hopper half angle of the discharge instrument used in this study is 15°, base on the result of calculated maximum hopper half angles, the samples in coarse particle region may performs mass flow and the samples in fine particle region may performs funnel flow, and some serious discharge problem will emerge if the particle size continues to decrease.

3.3Discharge result

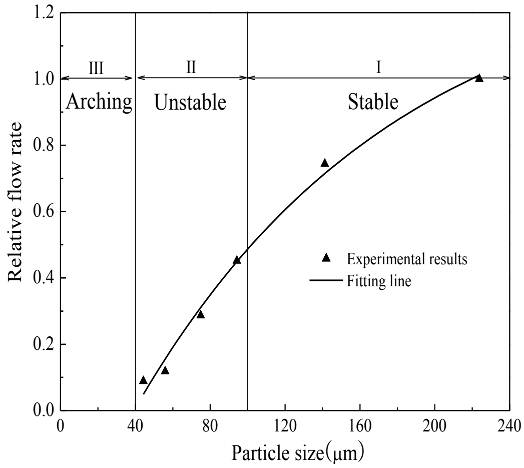

Fig. 14. Relative rate of discharge as a function of particle size

Fig14 shows the relationship between the relative flow rate and particle size of the pulverized coals. It is shows that the relative flow rate decreases exponentially with the decrease of particle size, which can be expressed as:

$$M = -1.826\exp(-\frac{d_v}{139.6}) + 1.379 \tag{10}$$

Where, M is the average relative flow rate, d_v is the equivalent volume diameter of the particles.

During the experimental process, a progressive transition from mass flow to unstable and to blocking was observed as the particle size decreased. Together with the analysis of weighting curves, three regions including mass-flow, unstable-flow, and arching were defined.

I. Mass-flow region (d_v>100μm).When opening the valve, all pulverized coals moves downwards towards the opening, which a typical mass flow patterns was obtained.

II. Unstable-flow region (40<d_v<100μm).When opening the valve, pulverized can discharge with a irregular flow rate by gravity and most of the flow patterns obtained were funnel flow, and a obvious indention can be obtained on the top of the solid bulk.

III. Arching region(d_v<40μm).When opening the valve, only a little powder dropped from the hopper, and stable cohesive arch was formed.

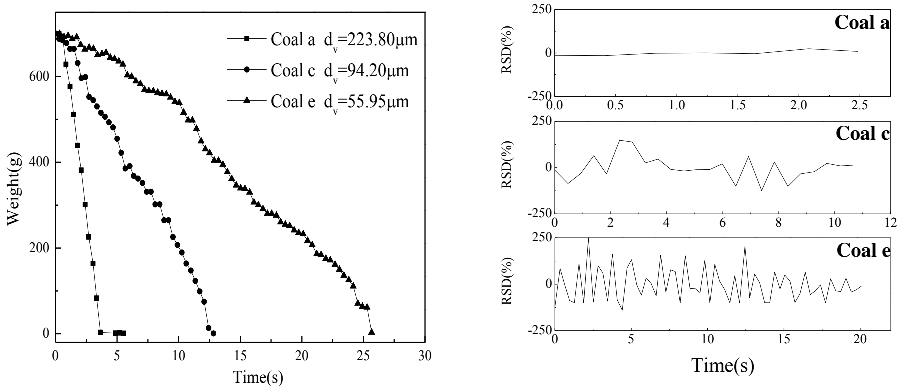

Fig. 15. (a) Residual mass as function of time for pulverized coal discharge (b) Relative standard deviation of flow rate

Three samples (sample a, c, e) represent mass flow region, boundary of mass and unstable flow region, and unstable flow region were selected to give the weighting curve and sequence of relative standard deviations of flow rate , as Fig 15 shows. The relative standard deviation of flow rate of pulverized coal ,a, fluctuates slightly and a powerful fluctuates was obtained for sample ,e, which accords with the classification of the flow regions observed during the experimental process.

Furthermore, the mass and unstable/arching flow region is equivalent to the fine and coarse particle region, respectively, which accords with the prediction given in section3.2. It is demonstrate that the effect of particle size on incipient flow and wall friction properties of pulverized coals will significantly increased when the particle size is smaller than a critical value (100μm for this study),in which the transmission efficiency of wall action and cohesive of solid bulk will significant increase with the decrease of particle size and hence results in unstable flow to even flow obstructions.

4. Conclusion

Pulverized coal from industry was used as the experimental material and sieved into seven samples with different particle size to study the effect on particle size on the flowability of pulverized coals. The failure and wall friction properties were determined by rotational shear method, and the Jenike's methodology is applied to predict the hopper discharge behaviour of samples. In the last section, the prediction was compared with the discharge test results. The observations of this study are summarized in the following conclusions:

- Consolidation caused a more compact packing structure of the bulk, and hence given larger interparticle force, by which the increase of macroscopic cohesive is obtained. But, the internal friction properties are not sensitive to consolidation.
- For the pulverized coals we studied, a critical particle size (100μm) is determined to classify the samples in coarse particle region and fine particle region. In the coarse region, the cohesive, angle of internal friction, and angle of wall friction are not sensitive to the effect of particle size; in contrast, the cohesive and angle of wall

friction increase significantly with the decreasing particle size. But, the angle of internal of internal friction is not sensitive to the change of particle size in both fine and coarse particle region.

- The pulverized coals belong to the complex powder which may shows different flow behavior due to the change of stress state. The flow problem such as unstable flow, or even flow obstructions obtained in fine particle region is due to the increasing transmission efficiency of wall action causing by the increase of interaction between particles and wall.

It has been noted previously that the flowablity of powders will decrease with the decreasing particle size, which leads to a series of flow problems. The investigation showed that the effect of particle size on the flow properties of pulverized coal is diversity and rheological test results can reflect flow properties of pulverized coal to some extent. But the shear test is base on the critical state model obtained from equilibrium of forces and a real flow is not happened. In addition, the adoption of fitting function have strong effect on the calculation of critical applied stress, sometimes, an large deviation is given.

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