Fuel 116 (2014) 131–139

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Theoretical and experimental investigation on angle of repose of biomass–coal blends

Zhiguo Guo, Xueli Chen, Haifeng Liu *, Qiang Guo, Xiaolei Guo, Haifeng Lu

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China

Shanghai Engineering Research Center of Coal Gasification, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China

HIGHLIGHTS

- A model has been proposed to determine the angle of repose for a single granule.
- A model on the angle of repose has been presented for binary granular system.
- The influencing factors of the angle of repose have been studied in detail.

ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 15 May 2013
Available online 14 August 2013

Keywords:
Angle of repose
Secondary particle
Base particle
Biomass–coal blends

ABSTRACT

The angle of repose of granular materials has been extensively studied, for it is a very important macroscopic parameter in characterizing the flowability of granular materials. The primary objective of the work is to develop a linear model, and to propose a quantitative expression about the angle of repose (Φ_R) of mixed granular system, which gives a qualitative understanding of the influence of physical parameters on mixed granular flow behavior. The results show that the variation amplitude of tangent Φ_R is linear with the related particle physical properties (density, particle size and secondary particle mass fraction). It is shown that the most important parameters determining the mixed granular system angle of repose are density variation and surface roughness for the similar particle size. In addition, whether the particle size of base particle material or secondary particle varies or not, the linear relationship always exists. And the slope k is determined primarily by particle shape and surface friction coefficient.

1. Introduction

Angle of repose (Φ_R) is one of the key factors in characterizing the flow behavior of granular materials. It is also related to many important phenomena, including avalanching, stratification and segregation [1–6]. Since the co-utilizations of biomass and coal can lead to the reduction of greenhouse gases emission, all kinds of these technologies attract more and more researchers' constant attention [7–9]. In the utilization process of biomass–coal blends, such as co-gasification and combustion in CFB system [10,11], the granular flowability not only influences the design of reactors and composition of the product gas but also has a significant effect on the continuous, stable, and controllable operation of the gasifier [12,13]. Therefore, the investigation of Φ_R on the binary mixed particles is of importance in characterizing powders flowability for industrial productions.

In general, the formation of Φ_R is attributed to the balance among the interparticle forces, interaction forces and gravity forces of the powders [14]. Up to present, the Φ_R of granular materials including biomass have been extensively studied through a number of experimental studies [15–20] which have found that the Φ_R highly depends on material properties such as particle size, shape and surface roughness of particle material. Lee and Herrmann [16] held the view that the Φ_R is strongly dependent on the friction coefficient μ but insensitive to other parameters of the granular system by establishing an implementation of static friction in a molecular dynamics simulation. In recent years, an empirical equation was given for predicting angle of repose as a function of the grain shape, size and sorting of the bed and ratio of particle diameter to average bed grain diameter by Miller and Byrne [21]. They found that the Φ_R increased with the decreasing of particle size, with the increasing of particle angularity and decreasing of sorting. However, qualitative description of the

* Corresponding author at: Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, East China University of Science and Technology, P.O. Box 272, Shanghai 200237, PR China. Tel.: +86 21 64251418; fax: +86 21 64251312.

E-mail address: hfliu@ecust.edu.cn (H. Liu).

0016-2361/$ - see front matter
http://dx.doi.org/10.1016/j.fuel.2013.07.098

Nomenclature

Φ_R	mixed granular system angle of repose, °
Φ_{RC}	a single composition particle angle of repose, °
h	the height of the particle slope, m
c	cohesion strength between particles, Pa
g	the particle gravitational acceleration, m/s^2
F_Z	sum of the adhesive forces, N
F_H	adhesive force between particles, N
A	area of the platen, m^2
n	number of particle contacts
d	single particle diameter
d_m	mixed granular mean diameter particle size, m
d_s	secondary particle diameter, m
d_b	base material diameter, m
k	slope of the linear model
A_0	granular material aspect ratio
C_1, C_2	two constants

Greek symbols

w	secondary particle mass fraction, %
φ	the angle of internal friction, °
ε	porosity of blends
ρ	single component particle density, kg/m^3
ρ_s	secondary particle density, kg/m^3
ρ_b	base material density, kg/m^3, kg/m^3
ρ_B	blends bulk density, kg/m^3
μ	particle surface friction coefficient
ψ	granular particle sphericity

dependence that can be used generally in engineering practice was not available.

Furthermore, there have been quite a few researches on characterizing flowability of pulverized coal [15,22] but few for biomass. Because of biomass substance construction and anisotropism in spatial structure, biomass material has irregular shape after the breakup of biomass particles. Thus the influence of biomass particle shape cannot be ignored in particle transport, mixing and fluidization. Some other studies [23–26] indicated that the biomass particle flowability is closely related with its shape in the utilization process. In addition, there are many industrial processes associated with mixed granular matter, such as the field of medicine [27] and energy sources [28–30]. Therefore, the mixed granular system will still be a hot field, and also attract more and more researchers' constant attention. However, the relevant literature on the Φ_R of binary mixed granular system is particularly scarce.

Consequently, a series of experiments were conducted to investigate the Φ_R of binary particles in this paper. A particle mixing criterion for binary mixture angle of repose had been developed and applied to more binary mixed granular systems including biomass–coal blends. The work would be helpful to the investigation of mixed particles system flow behavior and more directly useful to lay the root for the success of biomass–coal blends dense phase pneumatic conveying.

2. Theoretical approach

The interaction forces of the powder granular consist of Van der Waals forces, the capillary forces, electrostatic forces of the powders and so on. Considering the complex forces among particles, the following assumptions should be proposed. (1) Due to the lack of moisture content for materials, the capillary forces of particles could be ignored. (2) For mixed particles, the base material particle and secondary particle have a homogeneous mixing. (3) The particles are spherical.

Φ_R is defined as the angle of inclination of the free surface to the horizontal of a bulk solid pile when it is in a state of maximum static equilibrium. As shown in Fig. 1, the area of BDE will slip from inclined plan even under the action of the subtle vibration. Angle α can be considered as the minimum angle of repose which is equal to the angle φ.

Φ_R is measured with fixed-base piling method. The base radius (AC) is constant (see Fig. 1). Thus, we have

$$\tan \Phi_R = \frac{\mathrm{BC}}{\mathrm{AC}} = \frac{h}{l}. \tag{1}$$

As illustrated in Fig. 1, it can be seen that Φ_R depends on the height h of the slope for cohesive material. The height of a vertical slope, which applies to cohesion strength of particle is greater than 0, is given by [31]

$$h = \frac{4c\cos\varphi}{\rho_B g(1-\sin\varphi)}, \tag{2}$$

where c is the inter particle cohesion strength, ρ_B the bulk density of particle material and g the gravitational acceleration, with φ being commonly about 30° [31]. So, we have

$$h = \frac{4\sqrt{3}c}{\rho_B g}. \tag{3}$$

In order to simplify adhesive forces among particles, the cohesion strength c can be approximately regarded as the sum of the adhesive forces at a large number of particle contacts. In the following, the model is regarded on the basis of the van der Waals forces [32]. Then the adhesive force F_H is proportional to the particle diameter

$$F_H \propto d. \tag{4}$$

The cohesion strength c can be calculated from the tensile force at failure [32], F_Z, divided by the area of the platen A. Therefore

$$c = \frac{F_Z}{A}. \tag{5}$$

Now it is assumed that the force F_Z is the sum of the adhesive forces at the individual particle contacts in the failure plane. The number of contacts is n. And then

$$F_Z = nF_H. \tag{6}$$

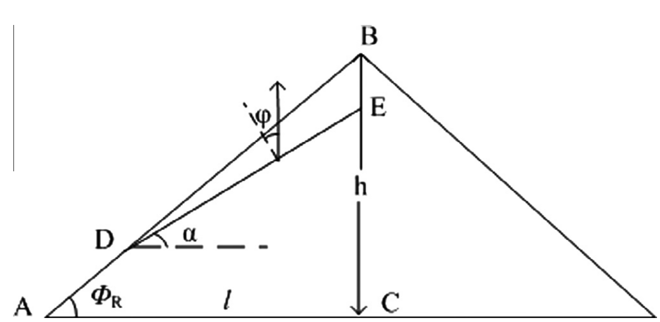

Fig. 1. Slip plane for the failure of a slope.

The number of particle contacts, n, is proportional to granular area and inversely proportional to the square of the particle diameter d. It can be expressed as

$$n \propto \frac{(1-\varepsilon)A}{d^2}. \tag{7}$$

According to Eqs. (4)–(7), we have

$$c = \frac{F_Z}{A} = \frac{nF_H}{A} \propto \frac{(1-\varepsilon)d}{d^2} \propto \frac{1-\varepsilon}{d}. \tag{8}$$

By definition, the porosity of granular system ε can be given as

$$\varepsilon = 1 - \frac{\rho_B}{\rho}, \tag{9}$$

where ρ_B and ρ are single component particle bulk density and apparent density, respectively. And substitute Eq. (9) into Eq. (8), the following expression could be obtained

$$c \propto \frac{\rho_B}{\rho d}. \tag{10}$$

And combining Eqs. (3) and (10) with Eq. (1), for ideal particle, Eq. (11) can be obtained.

$$\tan \Phi_{RC} \propto \frac{1}{\rho d}. \tag{11}$$

In order to modify Eq. (11) for a single component of particle, a constant C_1 should be introduced to characterize the non-ideal particle effects which have been confirmed by Halsey et al. [33]. Therefore, for a single kind particle, the tangent of angle of repose can be written as

$$\tan \Phi_{RC} \propto \frac{1}{\rho d} + C_1. \tag{12}$$

For mixed particle system, Eqs. (4)–(8) are also applicable to the granular system due to the previous assumptions. For needle-like particle, the particle sizes take the needle particle average width. Then diameter d_m is the mean particle size just as the following equation [34,35]

$$d_m = d_b(1-w) + d_s w, \tag{13}$$

where w is the secondary particle mass fraction, d_b and d_s are base particle and secondary particle diameter, respectively. By definition [36], the porosity of the mixed granular system can be approximated as

$$\varepsilon = 1 - \left[(1-w) \times \frac{\rho_B}{\rho_b} + w \times \frac{\rho_B}{\rho_s}\right], \tag{14}$$

where ε is the porosity of the mixed granular system, ρ_s and ρ_b are secondary particle and base particle apparent density, respectively. Then, substituting Eq. (14) into Eq. (8), the following expression could be obtained

$$c \propto \frac{\rho_B + \rho_B w\left(\frac{\rho_b}{\rho_s} - 1\right)}{\rho_b d} \tag{15}$$

With Eqs. (3) and (15) into Eqs. (1) and (16) can be rewritten as

$$\tan \Phi_R \propto \frac{1 + w\left(\frac{\rho_b}{\rho_s} - 1\right)}{\rho_b d_m}. \tag{16}$$

In order to modify the Eq. (16) for granular system, a constant C_2 should be introduced to characterize the non-ideal particle effects which have been confirmed by Halsey and Levine [33]. Therefore, for mixed granular system, the tangent of Φ_R can be written as

$$\tan \Phi_R \propto \frac{1 + w\left(\frac{\rho_b}{\rho_s} - 1\right)}{\rho_b d_m} + C_2. \tag{17}$$

Because of the relatively low quantity of secondary particle in the mixed granular system, the following assumptions are proposed. Firstly, the influence of secondary particles on the constants (including C_1 and C_2) is ignored. Secondly, after adding secondary particle to the base material, the variation of particle size is also ignored. Therefore, the variation amplitude of tangent of Φ_R ($\Delta \tan \Phi_R$) can be obtained by Eqs. (12) and (17)

$$\Delta \tan \Phi_R = \tan \Phi_R \tan \Phi_{RC} \propto \frac{\rho_b - \rho_s}{\rho_b \rho_s}\frac{w}{d_m} = k\frac{\rho_b - \rho_s}{\rho_b \rho_s}\frac{w}{d_m}. \tag{18}$$

The revised parameter k indicates the impact of other physical properties (shape, surface roughness) on the Φ_R of blends.

3. Experimental

3.1. Materials

Eight types of powders were used in the present work. The tested powders were: spherical glass beads with three different mean particle sizes; aluminium hydroxide; quartz sand; poly vinyl chloride (PVC); columnar particle; shenfu bituminous coal and two kinds of representative biomass (sawdust and rice straw). In order to form a series of mixed powder samples, part of particles were added to the glass beads (secondary particle maximum mass fraction to 30% in the study) which were used as base material to investigate the mixed blends Φ_R. Glass beads of different mean particle sizes were used in this work because their sphericity can reduce particle shape effects. Shenfu bituminous coal was crushed by a coal pulverizer FJ-6. Rice straw was obtained from the suburb of Shanghai in China and sawdust was from a furniture factory. Rice straw was smashed in a pulverizer FW177. Detailed physical properties of experimental material were listed in Tables 1 and 2.

3.2. Methods and equipment

As shown in Fig. 2, there are cumulative distribution functions of experimental material which were measured by a particle size analyzer of Malvern Mastersizer 2000. For needle-like particle, the particle sizes take the needle particle average width. Moisture content was measured by an infrared moisture meter MA150 which is produced by Sartorius of Germany. Since the moisture content is a key factor for the flow properties of powder [37], the moisture content of experimental material measured by an infrared moisture meter MA150 was controlled below 2%. BT-1000 powder synthetic characteristic tester was used to measure Φ_R. The Φ_R was gained from horizontal plane with the slope form an

Table 1
Material properties.

Material	Sample number	Sauter mean size (μm)	Moisture content (%)	ρ (kg/m^3)
Glass beads a	P1	56	0.67	2350
Glass beads b	P2	92	0.49	2350
Glass beads c	P3	332	0.34	2350
PVC a	P4	84	0.37	1340
PVC b	P5	136	0.41	1340
Quartz sand	P6	118	0.32	2650
Al_2O_3	P7	76	0.41	2150
Coal a	P8	16	1.80	1270
Coal b	P9	21	1.92	1270
Coal c	P10	40	1.30	1270
Coal d	P11	51	0.84	1270
Coal e	P19	34	1.26	1270
PVC c	P20	35	0.34	1340
Al_2O_3 a	P21	34	0.54	2150
Quartz sand a	P22	35	0.45	2650
Glass beads d	P23	37	0.42	2350

Table 2
Statistics of other columnar particles properties.

Sample number	Particle size (μm)	Moisture content (%)	Average length (μm)	Average width (μm)	Average A_0	ρ (kg/m^3)
Cylinder particle						
P12	600–2360	0.57	3820	600	8.55	1340
Rice straw						
P13	75–120	1.28	197	84	2.53	450
P14	120–180	1.36	436	146	4.12	450
P15	180–425	1.06	1327	237	8.71	450
Sawdust						
P16	75–120	1.81	326	155	2.32	600
P17	120–180	1.47	474	190	2.64	600
P18	180–425	1.15	658	233	2.82	600

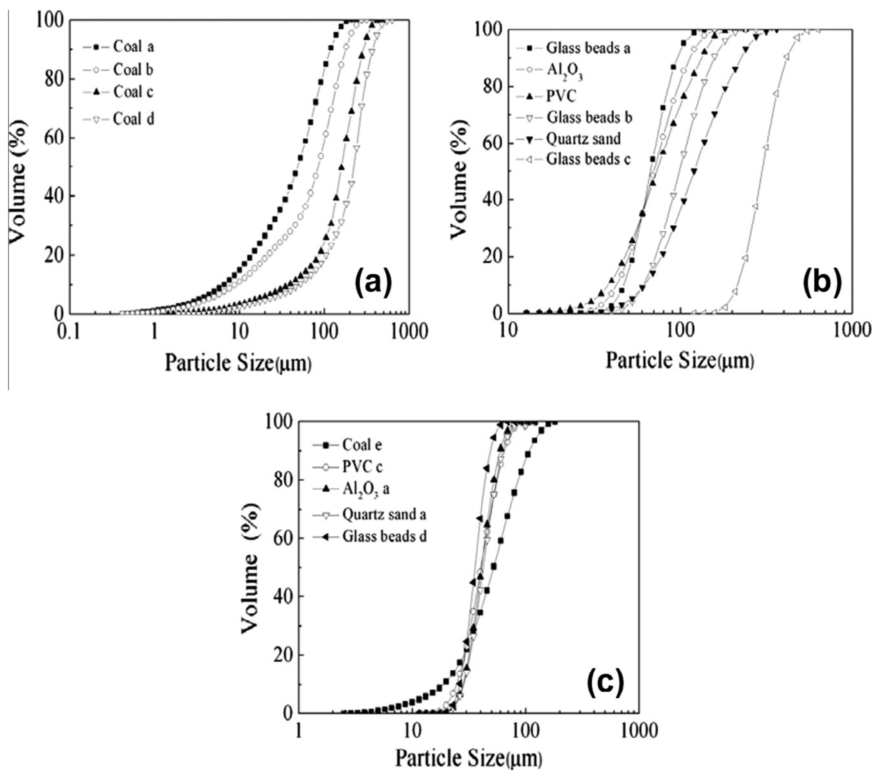

Fig. 2. The cumulative distribution functions of experiment material. (a) Shenfu coal (P8–P11). (b) Other common granules (P1–P7). (c) The granules with similar particle size (P19–P23).

angle just as the slope stable with fixed-base piling method. It should be noted that each Φ_R presented in this paper represents an average value of nine tests. The micro images of granular material were shot by scanning electron microscope (SEM). In the experiment, typical images were chosen to characterize the shape and surface roughness of particles as illustrated in Fig. 3.

4. Results and discussion

4.1. For a single composition particle

The properties of powders were listed in Table 1. Φ_R of the eleven kinds of particles (except for cylindrical particles) was measured in this part. After fitting the experiment results, the linear relationship is written as

$$\tan \Phi_{RC} = \frac{0.009}{\rho_d} + 0.607. \quad (19)$$

The correlation coefficient of Eq. (19) is 0.909 which indicates a strong linear relationship between $\tan \Phi_{RC}$ and $\frac{1}{\rho d}$. The linear relationship is found to agree well with Eq. (12). Furthermore, for a single composition particle, the linear relationship observed in Fig. 4a confirms that an increase of particle size is always accompanied by a decrease of the granular Φ_{RC}. Similar to results of many researchers [19–21], Φ_{RC} is strongly dependent on particle size. Meanwhile, it cannot negligible that particle density also has some impact on angle of repose. For the same particle size (see Fig. 2c), Fig. 4b shows the relationship between $\tan \Phi_{RC}$ and $\frac{1}{\rho}$ that the correlation coefficient is 0.807, which still agree well with $\tan \Phi_{RC} \propto \rho^{-1}$. Hence, it could be said that there is a relatively high correlation between the $\tan \Phi_{RC}$ and density. A higher density of particle means a greater gravity that can lead to a trend of its downward movement. The trend of motion can induce a smaller value of Φ_{RC}. The conclusion was put forward by few investigators. In the experiment, the coal particle $\tan \Phi_{RC}$ is larger than other experimental particles

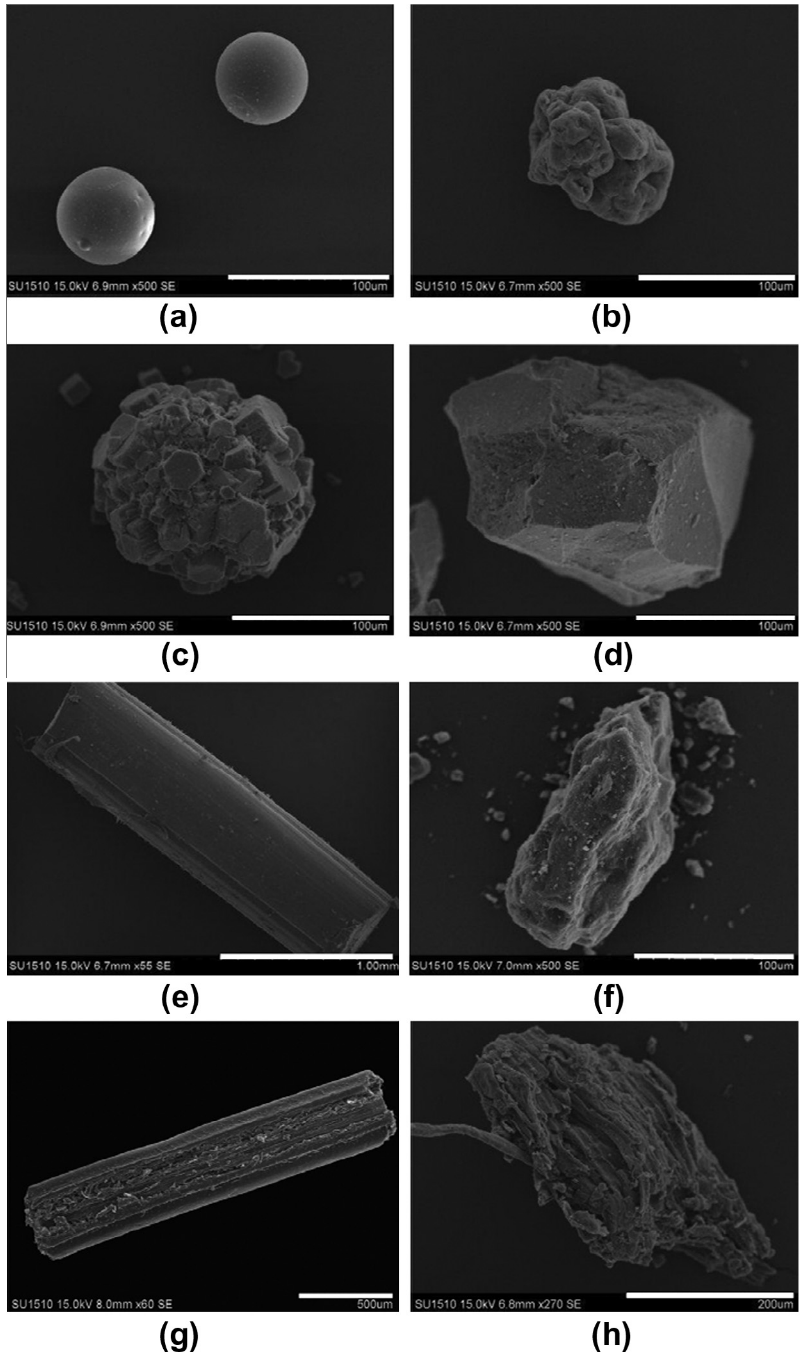

Fig. 3. Typical SEM images of granular material. (a) Glass bread. (b) PVC. (c) Al_2O_3. (d) Quartz sand. (e) String. (f) Coal. (g) Rice straw. (h) Sawdust.

which may show that the Φ_{RC} for rough surface particle is higher than that for the relatively smooth surface particle as illustrated in Fig. 4a. The similar conclusion has been demonstrated by many researchers [15–17].

4.2. Different base material particle size

The results of mixed particles were listed in Table 3. After fitting the experiment results of irregular needle (rice straw) particle adding into glass breads with different particle sizes, the linear relationship is written as

$$\tan \Phi_R = \frac{0.022}{\rho_b d_m} + 0.596. \tag{20}$$

The correlation coefficient of Eq. (20) is 0.902 which indicates a good linear relationship between $\tan \Phi_R$ and $\frac{\rho_s + w(\rho_b - \rho_s)}{\rho_b \rho_s d_m}$ for mixed particle system (see Fig. 5). The above relation also confirms that an increase of particle size is always accompanied by a decrease of the granular Φ_R. Compared Eqs. (19) and (20), the influence of secondary particle on the constants (including C_1 and C_2) can be ignored. It also can be confirmed that the above assumption between Eqs. (17) and (18) is reasonable. And then, based on above theoretical part and following experiment work, it can be concluded that Eq. (18) is reasonable.

The similar trend can be obtained in Fig. 6a–f in which the $\Delta \tan \Phi_R$ has a good linear relationship with $\frac{\rho_b - \rho_s}{\rho_b \rho_s} \frac{w}{d_m}$. After adding glass breads into PVC, $\Delta \tan \Phi_R$ and $\frac{\rho_b - \rho_s}{\rho_b \rho_s} \frac{w}{d_m}$ are both negatives that

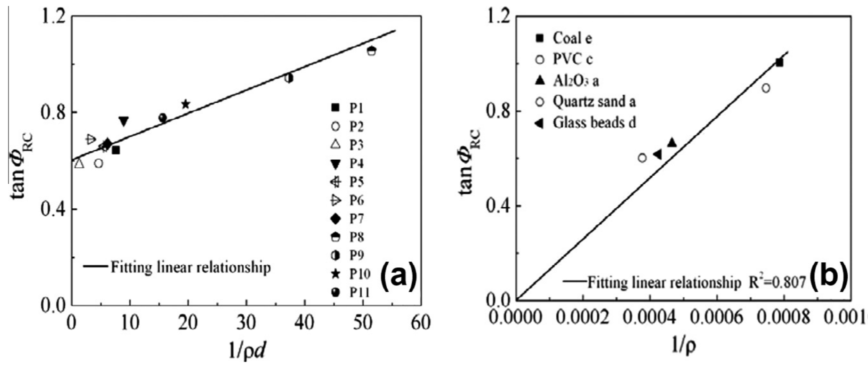

Fig. 4. The relationship between $\tan \Phi_{RC}$ and physical property. (a) $\tan \Phi_{RC}$ vs. $1/\rho d$. (b) $\tan \Phi_{RC}$ vs. $1/\rho$ for same particle size.

Table 3
Relationship between $\Delta \tan \Phi_R$ and $(\rho_b - \rho_s)w/\rho_b\rho_s\, d_m$.

The base material	The secondary particle	The slope k	R2
Fig. 6(a)			
P1	P18	0.0934	0.9084
P2	P18		
P3	P18		
Fig. 6(b)			
P1	P15	0.0229	0.9038
P2	P15		
P3	P15		
Fig. 6(c)			
P1	P12	0.0189	0.9251
P2	P12		
P3	P12		
Fig. 6(d)			
P1	P4	0.0464	0.9321
P2	P4		
P3	P4		
Fig. 6(e)			
P1	P6	0.122	0.9021
P2	P6		
P3	P6		
Fig. 6(f)			
P1	P7	0.175	0.9193
P2	P7		
P3	P7		
Fig. 6(g)			
P4	P1	0.052	0.9518
P5	P1		

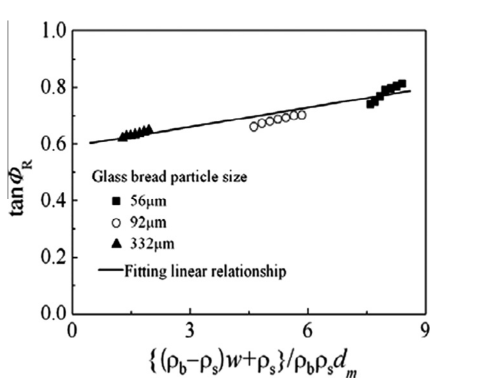

Fig. 5. The relationship between $\tan \Phi_R$ and $[(\rho_b - \rho_s)w + \rho_s]/\rho_b\rho_s d_m$.

the linear relationship also exists (see Fig. 6g). The experimental results correspond well to the theoretically calculated Eq. (18), but the slopes between them for diverse blends are different. The detailed results are shown in Table 3. An interesting phenomenon can be found that the slope k is not closely associated with particle size of glass breads. This may be due to horizontal ordinate which has contained the role of particle size.

Noticed that the angles of repose gradually increase as the mixed particle size decreases or with the increasing of mass fraction of secondary particle, indicating that both granular mixtures change from more free flowing to cohesive with these changes. Additionally, the influence parameter of Φ_R was emphasized on density variation, shape and surface roughness. In general, the Φ_R for rough surface particles was higher than that for the relatively smooth surface particles. And the same conclusion applies to the mixed particles which the Φ_R of sawdust and glass breads mixture is higher than Φ_R of rice straw and glass breads mixtures just as shown in Fig. 6h–i. PVC and string have the same density, but the shape and surface roughness is different.Fig. 6c–d suggest that PVC is more important to Φ_R than string which indicates the surface friction is important in controlling the angle of repose. The reason for the phenomenon is that surface friction means a large resistance force for granular material rotational motion, which presents an effective mechanism to consume the particle kinetic energy and stop its rotational motion, leading to the balance among the interparticle forces and formation of a sand pile [38]. When the quartz sand is added to glass breads, the secondary particle would be just like a same material with base material because of glass breads and quartz sand possessing the similar density and almost no segregation [39]. As can be seen in Fig. 6e–f, the little density variation means the smaller value of $\Delta \tan \Phi_R$. It is shown that density variation and surface roughness are the most important parameters in determining Φ_R of mixed granular material.

Due to the irregular shape of biomass and the rough surface of some particles (Al_2O_3 and quartz sand), the slopes of them are relatively larger than other mixtures. It is obviously observed in Fig. 6a–f that the slope k should be dependent on the shape and rough surface. The sharp change in Φ_R of mixtures occurs when particles have irregular shape and rough surface. Furthermore, the above two factors are of great importance in the flow characteristic of mixed particles system. That is to say, the k should be related to the surface friction coefficient μ and particle sphericity ψ.

4.3. Different secondary particle material particle size

The properties of powders were listed in Table 2. The slope k remains constant when secondary particle size is changed just as illustrated in Table 4. As shown in Fig. 6h–i, an interesting phenomenon can be found: $\Delta \tan \Phi_R$ has a good linear relationship with $\frac{\rho_b-\rho_s}{\rho_b\rho_s}\frac{w}{d_m}$ for biomass and coal blends, corresponding to the previous conclusion. Because of great differences between biomass and coal in physical properties, especially in surface roughness and shape, the mixtures Φ_R is larger with the increasing of biomass mass fraction. Apparently, sawdust with the rough surface has the

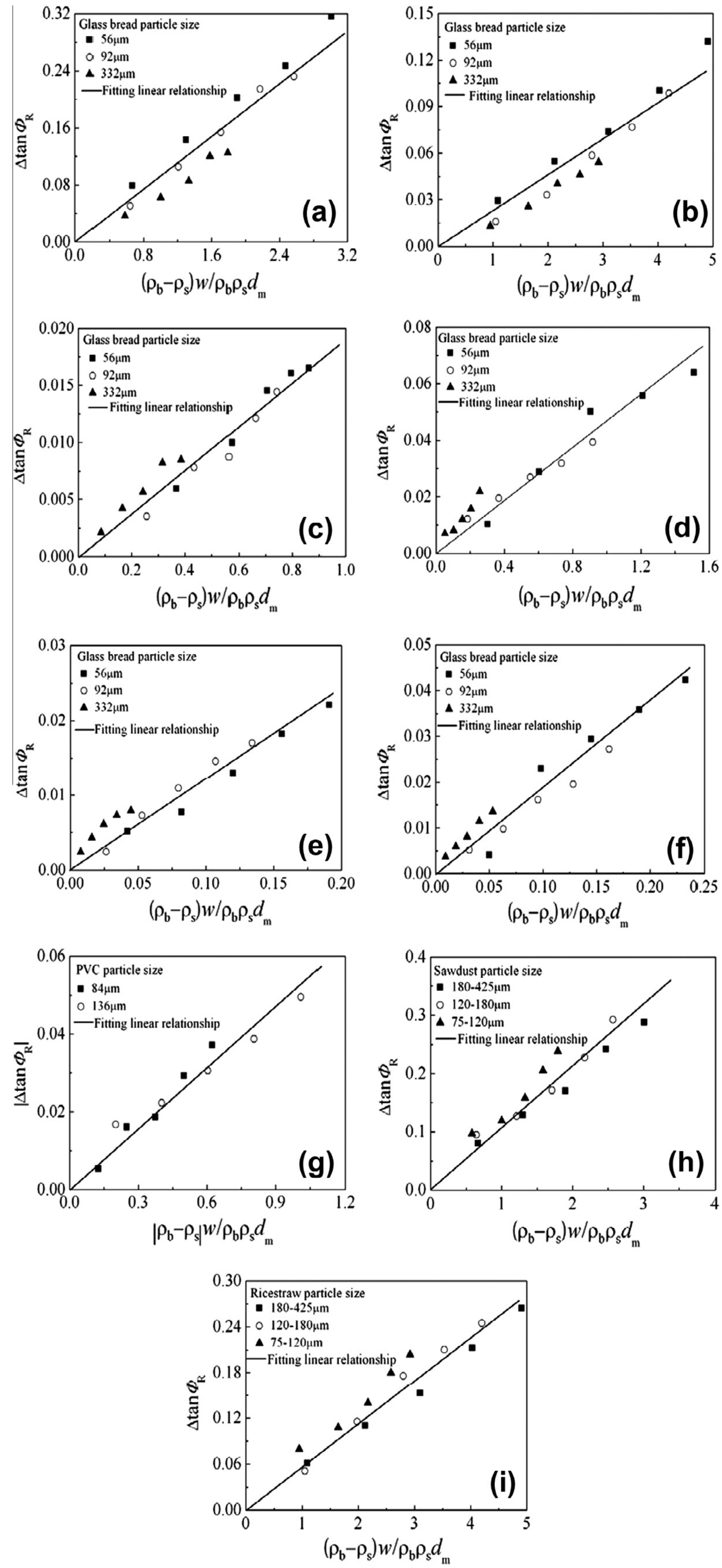

Fig. 6. Comparison of the variation of Φ_R for different mixed particle system. (a) Adding sawdust particles to glass beads. (b) Adding rice straw particles to glass beads. (c) Adding cylinder particles to glass beads. (d) Adding PVC particles to glass beads. (e) Adding quartz sand particles to glass beads. (f) Adding Al_2O_3 particles to glass beads. (g) Adding glass bead particles to PVC. (h) Adding sawdust particles to coal. (i) Adding rice straw particles to coal.

Table 4
Relationship between $\Delta \tan \Phi_R$ and $(\rho_b - \rho_s)w/\rho_b\rho_s\, d_m$.

The base material	The secondary particle	The slope k	R2
Fig. 6(h)			
P8	P16	0.107	0.8857
P8	P17		
P8	P18		
Fig. 6(i)			
P8	P13	0.0558	0.9150
P8	P14		
P8	P15		

larger friction forces just as shown in Fig. 3g–h. The aspect ratio is introduced to characterize the irregular shape of biomass. Similar to Guo's [25] conclusion, aspect ratio is corresponding with the particle size that it is increasing with the increasing of biomass particle size (see Table 2). The conclusion was found that Φ_R of blends including sawdust is larger than blends of rice straw for the same particle size. Though the sawdust has the lower aspect ratio and larger surface roundness, the flowability of blends for sawdust is weaker.

However, it should be noted that the smaller biomass particle size leads to the lower Φ_R, which results in better flowability. The smaller particle size, the lower aspect ratio is. This may be the reason why the smaller biomass particle size of blends has a lower Φ_R. The slope k for sawdust and coal is larger than rice straw and coal. It is mainly due to the sawdust rough surface. In addition, the rice straw's shape is needle-like while sawdust has the rough surface as shown in Fig. 3g–h. That is why sawdust plays a more role on the angle Φ_R of blends. The slope k should be related to the aspect ratio instead of sphericity for slender or cylindrical particles.

It is important that the study combine the investigation of Φ_R with flowability of binary particle system. The criteria for characterizing the granules flowability is as follows: Carr [40] put forward the empirical theory that the angle Φ_R below 30° indicated good flow-ability, 30–45°some cohesiveness, 45–55° poor flow, and >55° barely flow. For biomass–coal blends, the Φ_R largely lies from 40° to 50°. It means that the biomass–coal blends can be classified as "poor flowing" to some certain extent.

5. Conclusions

The present study was focused on the influence of the addition of secondary particle to the base material on the Φ_R of binary particle system. The following conclusions have been developed:

(1) For a single kind particle (except for the particle having large aspect ratio), the tangent of Φ_{RC} can be written in the form

$$\tan \Phi_{RC} \propto \frac{1}{\rho d} + C_1. \tag{21}$$

(2) For mixed granular system including base particle and secondary particle, combining the partial-theoretical formula (derived from inter particle forces) and related experiment work, a quantitative expression is obtained as follows:

$$\Delta \tan \Phi_R = \tan \Phi_R - \tan \Phi_{RC} \propto \frac{\rho_b - \rho_s}{\rho_b \rho_s} \frac{w}{d_m} = k \frac{\rho_b - \rho_s}{\rho_b \rho_s} \frac{w}{d_m} \frac{w}{d_m}. \tag{22}$$

Whether the particle size of base particle material or secondary particle varies or not, the linear relationship always exists. These measurements indicate that the angle of repose of blends has a better linear relationship with the secondary particle mass fraction w. The slope k is mainly dependent by particle shape and surface friction coefficient.

(3) It is shown that the most important parameters determining the Φ_R of mixed granular material are density variation and surface roughness for the similar particle size, indicating that the slight variation of density and the lower surface roughness between secondary particle material and base material means a better flow characteristic of mixed particles.

(4) Finally, it should be pointed out that this work is mainly a preliminary study. Some analyses have to be based on simplified or ideal considerations. This study put emphasis on the static properties of secondary particle and base material blends. The further research on dynamical behaviors of blends (biomass–coal) in the dense phase pneumatic system is needed. This also points out the direction of our future work.

Acknowledgements

This study was supported by the National Key Technologies R&D Program (2012BAA09B02), the National Natural Science Foundation of China (21176079), the National Development Programming of Key Fundamental Researches of China (2010CB227005), the Fundamental Research Funds for the Central Universities, and Program for New Century Excellent Talents in University (NCET-12-0854).

References

[1] Frette V, Christensen K, Malthesorenssen A, Feder J, Jossang T, Meakin P. Avalanche dynamics in a pile of rice. Nature 1996;379:49–52.
[2] Jaeger H, Liu C, Negel S. Relaxation at the angle of repose. Phys Rev Lett 1989;62:40–3.
[3] Makse HA, Havlin S, King PR, Stanley HE. Spontaneous stratification in granular mixtures. Nature 1997;386:379–81.
[4] Baxter J, Tuzun U, Heyes D, Hayati I, Fredlund P. Stratification in poured granular heaps. Nature 1998;391:136.
[5] Jullien R, Meakin P, Pavlovitch A. Particle size segregation by shaking in two-dimensional disc packings. Europhys Lett 1993;22:523–8.
[6] Samadani A, Kudrolli A. Angle of repose and segregation in cohesive granular matter. Phys Rev E 2001;64:1301–10.
[7] Hein KRG, Bemtgen JM. EU clean coal technology-co-combustion of coal and biomass. Fuel Process Technol 1998;54:159–69.
[8] Prabir B, James B. Studies on the operation of loop-seal in circulating fluidized bed boilers. Appl Energy 2009;86:1723–31.
[9] Nikolopoulos A, Nikolopoulos N, Charitos A, Grammelis P, Kakaras E, Bidwe A, et al. High-resolution 3-D full-loop simulation of a CFB carbonator cold model. Chem Eng Sci 2013;90:137–50.
[10] Sami M, Annamalai K, Wooldridge M. Co-firing of coal and biomass fuel blends. Prog Energy Combust Sci 2001;27:171–214.
[11] Pedersen LS, Nielsen HP, Kiil S, Hansen LA, Johansen KD, Kildsig F, et al. Full-scale co-firing of straw and coal. Fuel 1996;75:1584–90.
[12] Huang W, Gong X, Guo X, Dai Z, Liu H, Cao Z, et al. Study of the pressure drop of dense phase gas-solid flow through nozzle. Powder Technol 2009;189:82–6.
[13] Huang W, Gong X, Guo X, Dai Z, Liu H, Zheng L, et al. Discharge characteristics of cohesive fine coal from aerated hopper. Powder Technol 2009;194:126–31.
[14] Wang W, Zhang J, Yang S, Zhang H, Yang H, Yue G. Experimental study on the angle of repose of pulverized coal. Particuology 2010;8:482–5.
[15] Lu H, Guo X, Gong X, Huang W, Ma S, Wang C, et al. Study of the flowability of pulverized coals. Energy Fuels 2009;23:5529–35.
[16] Lee J, Herrmann HJ. Angle of repose and angle of marginal stability: molecular dynamics of granular particles. J Phys A: Math Gen 1993;26:373.
[17] Ileleji KE, Zhou B. The angle of repose of bulk corn stover particles. Powder Technol 2008;187:110–8.
[18] Carstensen J, Chan P. Relation between particle size and repose angles of powder. Powder Technol 1976;15:129–31.
[19] Zhou Y, Xu B, Xu A, Zulli P. An experimental and numerical study of the angle of repose of coarse spheres. Powder Technol 2002;125:45–54.
[20] Carrigy MA. Experiments on the angles of repose of granular materials. Sedimentology 1970;14:147–58.
[21] Miller RL, Byrne RJ. The angle of repose for a single grain on a fixed rough bed. Sedimentology 2006;6:303–14.
[22] Standish N, Yu AB, He Q. An experimental study of the packing of a coal heap. Powder Technol 1991;2:187–93.

[23] Cleary PW. The effect of particle shape on simple shear flows. Powder Technol 2008;179:144–63.
[24] Zulfiqar M, Moghtaderi B, Wall TF. Flow properties of biomass and coal blends. Fuel Process Technol 2006;87:281–8.
[25] Guo Q, Chen X, Liu H. Experimental research on shape and size distribution of biomass particle. Fuel 2012;94:551–5.
[26] Nehru C, Alvin R, Venkata SP. Flowability parameters for chopped switchgrass, wheat straw and corn stover. Powder Technol 2009;193:79–86.
[27] Wu C, Ruddy OM, Bentham AC. Modelling the mechanical behavior of pharmaceutical powders during compaction. Powder Technol 2005;152:107–17.
[28] Dai J, Sokhansanj S, Grace JR, Bi X, Lim J, Melin S. Overview and some issues related to co-firing biomass and coal. Can J Chem Eng 2008;86:367–86.
[29] Julia H, Göran B, Filip J, Jan K. Co-firing biomass with coal for electricity generation-An assessment of the potential in EU27. Energy Policy 2009;37:1444–55.
[30] Maciejewska A, Veringa H, Sanders J, Peteves SD. Co-firing of biomass with coal: constraints and role of biomass pre-treatment. The Netherlands: Institute for Energy; 2006.
[31] Nedderman RM. Statics and kinematics of granular materials. London: Cambridge University Press; 1992. p. 38–40.
[32] Dietmar S. Powders and Bulk Solids: Behavior, Characterization, Storage and Flow. Berlin, Heidelberg: Springer-Verlag; 2007. p. 32–4.
[33] Halsey TC, Levine AJ. How sandcastles fall. Phys Rev Lett 1998;14:3141–4.
[34] Artega P, Tüzün U. Flow of binary mixtures of equal-density granules in hoppers-size segregation, flowing density and discharge rates. Chem Eng Sci 1990;45:205–23.
[35] Humby S, Ttiztin U, Yu AB. Prediction of hopper discharge rates of binary granular mixtures. Chem Eng Sci 1998;53:483–94.
[36] Yu AB, Standish N, Lu L. Coal agglomeration and its effect on bulk density. Powder Technol 1995;82:177–89.
[37] Liang C, Chen XP, Xu P, Liu B, Zhao CS, Xu CL. Effect of moisture content on conveying characteristics of pulverized coal for pressurized entrained flow gasification. Exp Therm Fluid Sci 2011;35:1143–50.
[38] Zhou YC, Wright BD, Yu AB. Rolling friction in the dynamic simulation of sandpile formation. Physica A 1999;269:536.
[39] Jain N, Ottino JM, Lueptow RM. Regimes of segregation and mixing in combined size and density granular systems: an experimental study. Granul Matter 2005;7:69–81.
[40] Carr RL. Evaluating flow properties of solids. Chem Eng 1965;72:163–8.