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## Impact of particle density on the classification efficiency of the static air classifier in Vertical Spindle Mill

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**Abstract:** In order to investigate the impact of density on the classification behavior of particles in the static classifier of Vertical Spindle Mill, the sensitivity of overflow yield to the increase of air amount for narrowly sized pyrite, carborundum, quartz and coal samples were compared in a lab-scale classifier, respectively. Response surface methodology is used to analyze the combined effect of size and density on the classification. Wide size classification was also conducted and results show that both the yield and R90 of overflow increase with the decreasing of density, and the growth of air amount would also lead them to rise. The Whiten's model was applied to illustrate the influence of density on the sharpness of classification, corrected cut size and fishhook effect. Results show that material with a lower density would have a higher fishhook effect parameter, classification sharpness and corrected cut size. The increase of air amount would result in a more evident fishhook effect for the high density material. Based on the Whiten's model, a new classification efficiency model with the addition of particle density in various forms was established. This new model could describe the classification efficiency of materials with different density in the identical experiment conditions.

**Keywords:** static air classifier, classification efficiency, material density

### 1. Introduction

In the pulverizing process of coal power plant, air classifier controls the fineness of Pulverized Fuel (PF). To ensure the qualified PF could react effectively with oxygen in the furnace, typically the coal particles need to be at least 80% finer than 90  $\mu\text{m}$ , with 99.5% of particles in the size of <math>-300 \mu\text{m}</math>. As classifier is usually directly installed upon the mill table, its performance definitely would affect the grinding efficiency of mill (Xie, 2016).

For the classifier system in the mill, several models for classification were developed to evaluate the performance of air classifier. Kis et al. (2005, 2006) has established discrete mathematical models for the simulation and optimizing design on the basis of distributed parameter models of continuous grinding processes. Sato et al. (1996) investigated classifier parameters empirically, and obtained functions for classification efficiency and cut size dependent on the classifier geometry. Based on data of on-line sampling, a mathematical modeling was constructed by Shi and Kojovic for the classifier, incorporating coal-specific and machine-dependent variables in the Sproull's gas cyclone model (Shi et al., 2015; Kojovic et al., 2015). Also, Wei et al. established the parameters optimization model about classification efficiency of an industrial mill (Wei et al., 2014). On the other hand, with the help of numerical simulation, classification behavior of different size coal particle within air classifier was revealed by comparing trajectories (Bhasker, 2002; Vuthalurn et al., 2005), and the optimization of classifier was

conducted by adjusting vane settings (Parham et al., 2003; Shah et al., 2009) and designing plate positions (Ataş et al., 2014).

No matter mathematical modeling or numerical simulation, researches on the classification of air classifier in the mill mentioned above all treated coal as a pure material with a certain density, so the size-by-size efficiencies could be calculated to evaluate the performance of classifier. In fact, the quality of coal for power generation is relatively poor considering the economic level. Coal usually associates with other minerals, most of which have been liberated from coal after being ground to minor than 90  $\mu\text{m}$  (Shi et al., 2011; Wang, 2013). As a result, classifier feed consists of particles with density ranging from -1.3 to +1.8  $\text{g}/\text{cm}^3$ , which has been proved by research of Li et al. (2016). Thus, their calculation is likely inaccurate. Özer firstly noticed the necessity of considering material density while evaluating classifier efficiency. So he conducted aerodynamic classification function which illustrated the relationship of efficiency with settling velocities of particles when he investigated the classification operation in a coal pulverizer (Özer et al., 2010; Özer, 2011). Altun et al. also illustrated the importance of material density in a dynamic classifier though correlating density to the parameters, such as corrected cut size and bypass fraction, of Whiten's equation according to classification results of coal, clinker, copper ore and magnetite (Altun et al., 2016).

In this paper, in order to reveal the influence of particles density on the classification behavior, sensitivities of narrowly sized minerals with different density to the growing of air amount were compared and response surface methodology was applied to demonstrate the combination effect of size and density in a lab-scale static classifier. Classification results of materials in wide size were fitted by Whiten's model, respectively. And a new model, containing both material size and density, was established to illustrate the difference in classification effect of multi-component particles within classifier.

## 2. Materials and methods

### 2.1. Experimental system

Experimental tests were conducted with a laboratory classification system which is shown in Fig. 1. This system includes devices of air supply, classification and collection. Feed rate was controlled by a screw feeder, and the air amount could be adjusted by air valve and monitored by a flow meter. Within this study, 300 g material was added in and the classification time was set as 5 min in each classification experiment.

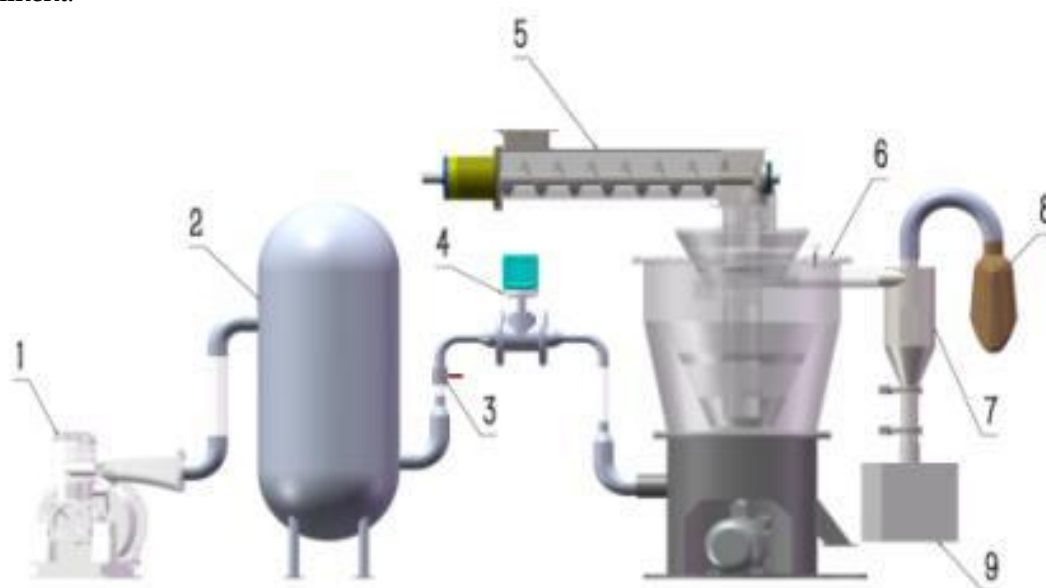


Fig. 1. Schematic diagram of the experimental system of classifier  
(1. Blower; 2. Air tank; 3. Valve; 4. Flow meter; 5. Screw feeder; 6. Classifier; 7. Cyclone separator; 8. Bag dust collector; 9. Aggregate tank)

## 2.2. Experimental materials

Coal, quartz, carborundum and pyrite were selected as experimental material, with density of 1.25, 2.60, 3.40, 4.60 g/cm<sup>3</sup>, respectively. The ash content of coal is just 3.96%, containing little minerals. And the X-ray diffraction spectrograms of pure minerals are shown in Fig. 2. It indicates that all of them could be treated as material with homogeneous density. Coal, quartz, carborundum and pyrite was crushed and screened into -200+125, -125+90, -90+63, -63+45 and -45 μm size fractions, respectively. About 20 groups of narrow sized materials were prepared for comparing sensitivity of overflow yield along with growing of air amount.

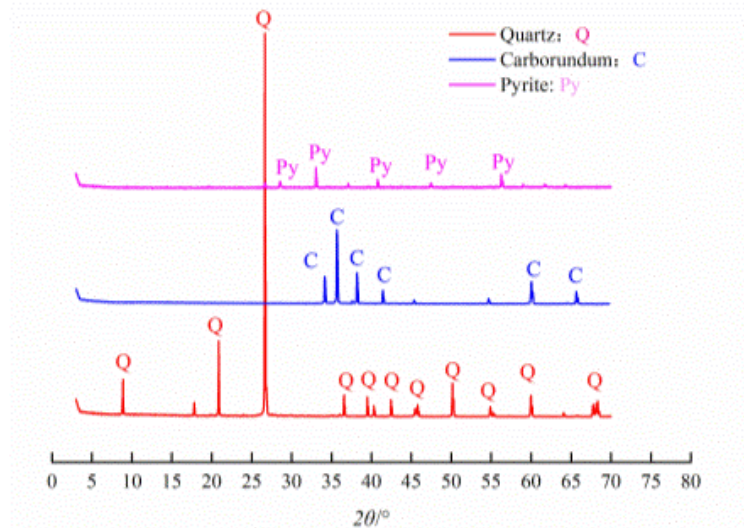


Fig. 2. X-ray diffraction spectrograms of pure minerals

The classification of particles in the wide size fraction was also carried out to illustrate the impact of density on the overall. The narrowly sized particles of coal were mixed at equivalent mass, and quartz, carborundum and pyrite were the same way, respectively, which could ensure the size distribution of classifier feed is consistent. After classification, each overflow product was collected, weighed and its size distribution was measured applying laser particle analyzer.

## 3. Results and discussion

### 3.1. Sensitivity of overflow yield for narrowly sized minerals

Sensitivity is an index for evaluating the response of narrowly sized along with air amount rising. The calculation equation is given:

$$I = \Delta Y / \Delta V_g \quad (1)$$

where  $\Delta Y$  and  $\Delta V_g$  are the increment of overflow yield and air amount, respectively.

Fig. 3 shows the sensitivity of narrowly sized minerals. For particles in the size fraction of -200+125 μm,  $I$  value of each material gradually grows, which indicates that the influence of air amount becomes notable. Besides,  $I$  value ranks based on density, and that of coal is much higher than those of others. It means that overflow yield of material with lower density is much sensitive to the change of air amount. For minerals in size fraction of -125+90 μm,  $I$  value of coal sees a long linear decrease, while that of silicon sees a short linear increase. Finally, they meet at a stable value with a larger air amount, and those of denser minerals keep growing along with air amount.  $I$  values of coal, silicon and carborundum with size fraction of -90+63 μm gradually decrease to a minimum point then begin to increase, which is opposite to the variation tendency of pyrite. For the micro-size fraction of minerals,  $I$  values are approaching as the air amount grows. And change rule of  $I$  values for pyrite also turns to the same as those of other three. Due to the differences in gravity force and centrifugal force among particles with different density, sensitivity of narrowly sized minerals along with the growing of air amount is not the same, which leads to different overflow yields.

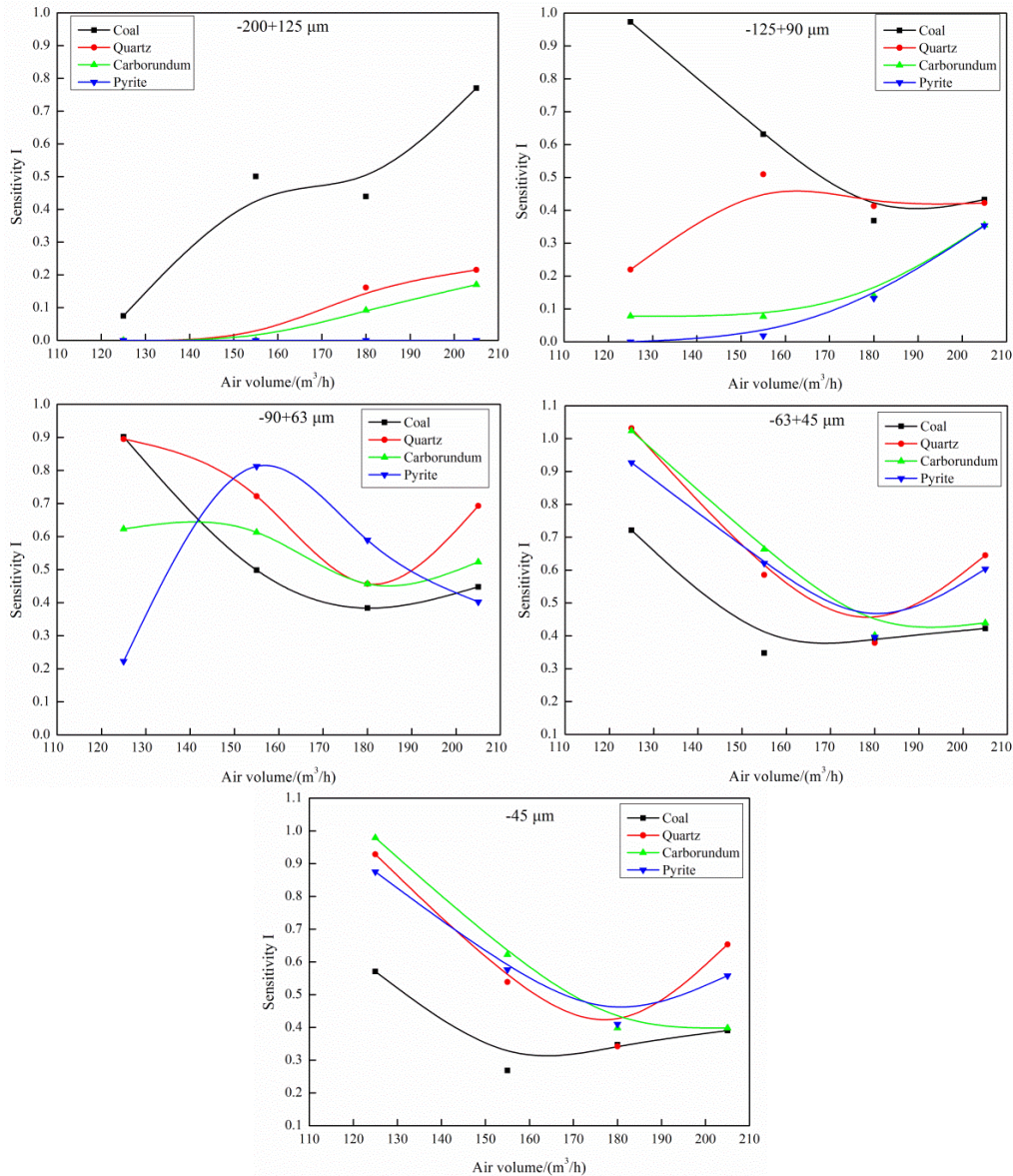


Fig. 3. Sensitivity of overflow yield with air amount for different size minerals

Based on classification test results of narrowed size minerals, response surface methodology is applied to emphasize analyze the combination effect of particle size and density on the overflow yield, which is illustrated in Fig. 4.

Surface response clearly shows that the overflow yields of the coarser and denser particles are much lower than the smaller and lighter ones at a certain air amount. That is to say, combination effect of particle size and density has significant impact on overflow yield. Particle density definitely cannot be ignored if the classification effect being evaluated. A quadratic model is established to simply describe the relationship among air amount, particle size and density and overflow yield. And the variance analysis of this quadratic model is listed in Table 1.

The *F* value of 78.82 indicates that the model is significant. Values of Prob>*F* less than 0.0500 represent that a model term is significant. Based on this criterion, particle size, density and air amount are all significant model terms. The quality of the obtained model is evaluated by assessing the significance of the regression coefficients using Student's *t*-test. The *R*<sup>2</sup> value for the model is found to be 0.99, representing an acceptable agreement between the experimental results and the calculated values from the suggested model.

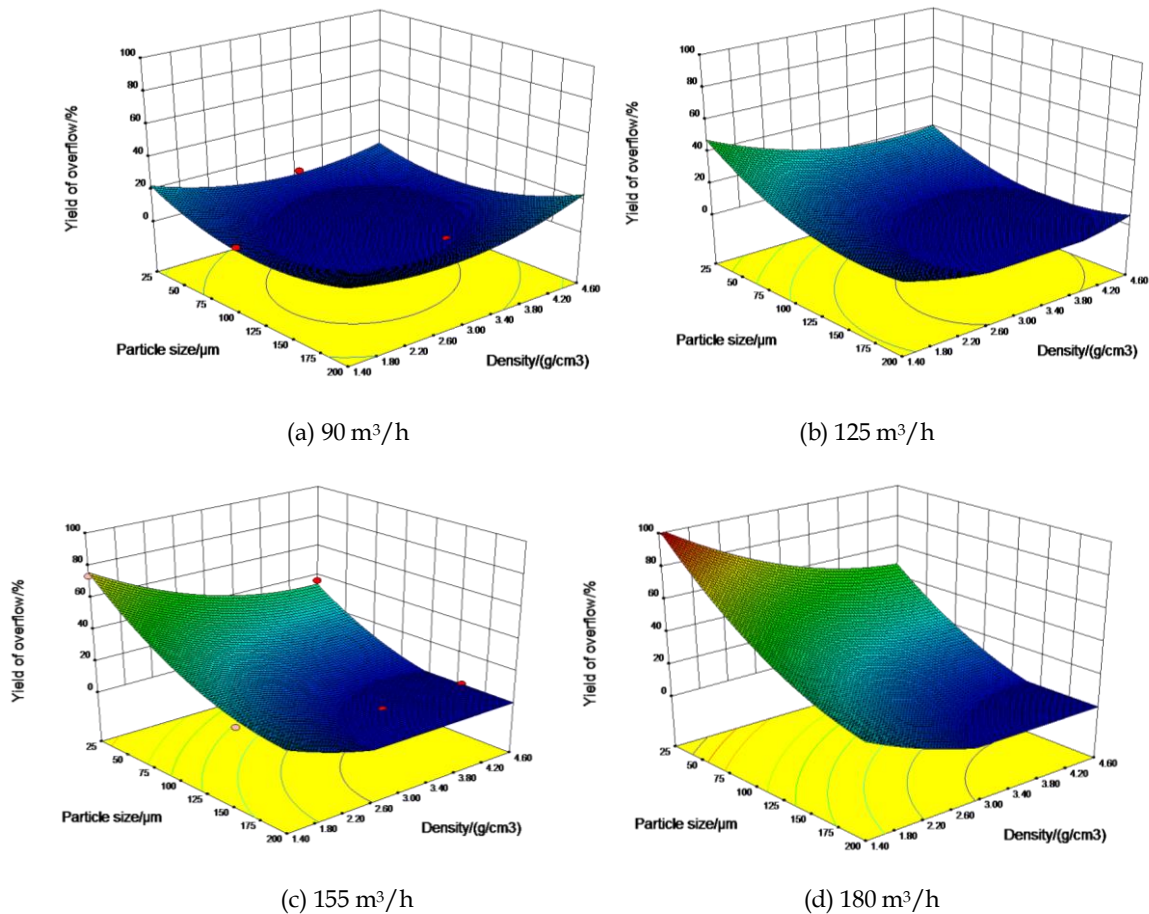


Fig. 4. Combination effect of size and density on overflow yield

Table 1. Variance analysis of the quadratic model

Source	Sum of squares	Degree of freedom	Mean squares	F-value	Prob > F	
Model	13649.35	9	1516.59	78.82	< 0.0001	significant
A-size	974.38	1	974.38	50.64	0.0002	
B-density	1371.49	1	1371.49	71.28	< 0.0001	
C-air amount	2802.72	1	2802.72	145.67	< 0.0001	
AB	73.34	1	73.34	3.81	0.0919	
AC	1195.63	1	1195.63	62.14	0.0001	
BC	716.04	1	716.04	37.22	0.0005	
A <sup>2</sup>	186.34	1	186.34	9.68	0.0170	
B <sup>2</sup>	434.28	1	434.28	22.57	0.0021	
C <sup>2</sup>	351.87	1	351.87	18.29	0.0037	
Residual	134.68	7	19.24			
Lack of Fit	134.68	4	33.67			
Pure Error	0.00	3	0			
Cor Total	13784.03	16				

### 3.2. Comparison of overflow product for wide size classification

The yield and fineness of overflow for classification with wide size fraction is compared in Fig. 5. When air amount is at 125 m<sup>3</sup>/h, coal (low density) achieves the highest overflow yield, reaching to 42%, which

is about 25% higher than that of pyrite (high density). However, the fineness of the overflow product obtained from the high density material is significantly smaller than that of the low density. More specifically, the  $R_{90}$  of pyrite is less than 10%, while  $R_{90}$  of silicon, quartz and coal are 20.81%, 25.66% and 28.36%, respectively. The large differences in yield and fineness among the overflow products fully prove that density of classified material has an evident impact on the overall classification effect.

As air amount increases to 155 m<sup>3</sup>/h, both the yield and fineness of coal, quartz, carborundum and pyrite all present an increasing trend, the highest variation occurs to coal. The overflow yield of coal grows by almost 20%, and its  $R_{90}$  increases by almost 8%. As a result, for the same material, with the air amount rising, the overflow yield increases, but the fineness becomes coarser.

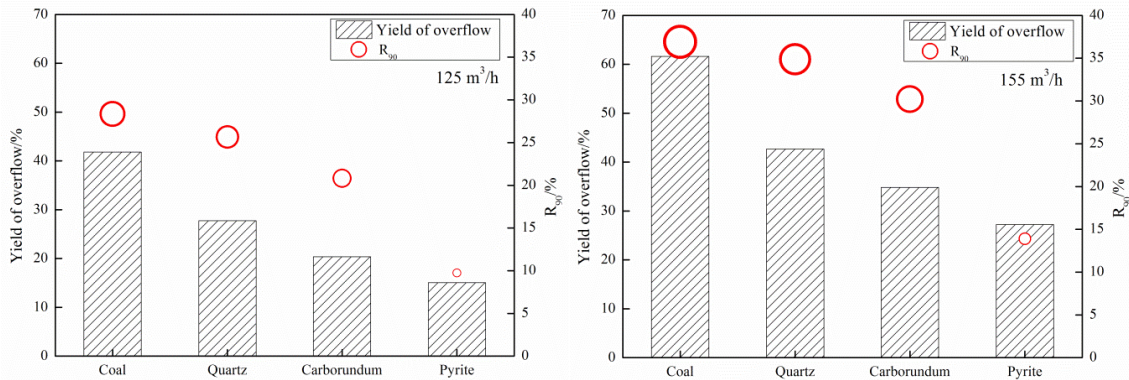


Fig. 5 Comparison of overflow yield and fineness for classification

### 3.3. Classification efficiency

The classification efficiency of each material is calculated by the following equation:

$$E_{oai} = 100 \times \frac{W_o(d_i) \times M_o}{W_f(d_i) \times M_f} \tag{2}$$

where  $E_{oai}$  is the actual classification efficiency to overflow,  $W_o(d_i)$  and  $W_f(d_i)$  are the mass fraction of the material with particle size  $d_i$  in the overflow and feed, respectively.  $M_o$  and  $M_f$  are the mass of overflow and feed, respectively. The classification efficiency curves for the four pure materials with wide size fraction are shown in the Fig. 6.

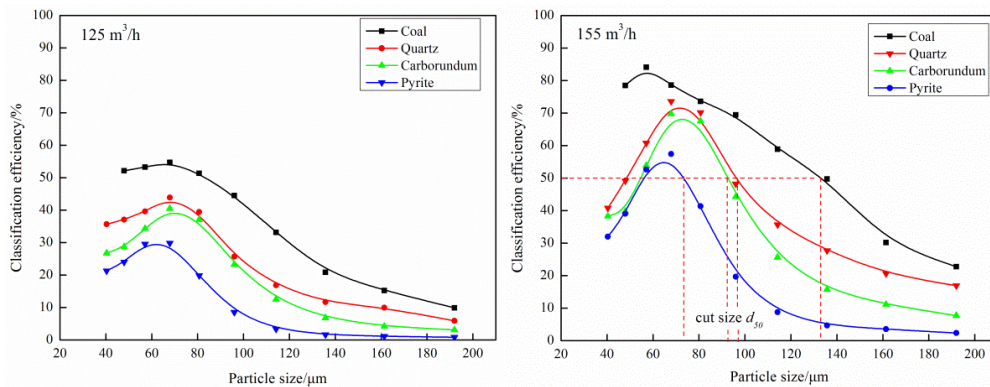


Fig. 6. Actual classification efficiency curves

As shown in Fig. 6, size-by-size classification efficiency has significant differences as densities are different, decreases gradually from the lightest to the heaviest material. The shape of all the classification efficiency curves is similar. As the particle size grows, the classification efficiency increases firstly and then decreases. The maximum classification efficiency of coal reaches to 54.74% which is about 10% higher than that of quartz, and those of carborundum and pyrite are 40.50% and 29.84%, respectively. The classification efficiencies of high density materials, such as carborundum and pyrite,

appear an obvious fish-hook effect. However, this phenomenon is not notable for low density materials, such as coal and quartz.

Table 2. Fitting results of parameters applying Whiten's model

Air amount /(m <sup>3</sup> /h)	Material	Parameter				R <sup>2</sup>
		$\beta$	$\beta^*$	$a$	$d_{50c}/\mu\text{m}$	
125	Coal	107.81	1.29	1.81	83.30	0.99
	Quartz	78.19	0.91	2.60	64.40	0.97
	Carborundum	59.94	0.62	5.91	55.30	0.97
	Pyrite	41.59	0.54	8.44	43.00	0.97
155	Coal	156.80	2.83	0.92	132.00	0.99
	Quartz	118.96	1.07	2.87	92.60	0.95
	Carborundum	98.90	0.89	6.15	86.00	0.95
	Pyrite	75.39	0.86	8.86	73.10	0.96

Classification efficiency of four materials all increases in different degrees as air amount rises to 155 m<sup>3</sup>/h. The maximum classification efficiency of coal is more than 80%. Those of quartz and carborundum are close, about 70%, nearly 15% higher than that of pyrite. Besides, another important index for evaluating the performance of classifier, cut sizes of coal, quartz, carborundum and pyrite are 133, 97, 93 and 73  $\mu\text{m}$ , respectively, decreases obviously with the increase of material density. The fish-hook effect of classification efficiency curve of pyrite still appears at 63  $\mu\text{m}$  nearby, slightly smaller than the size of quartz and carborundum, near 72  $\mu\text{m}$ . The classification efficiency curve of coal decreases monotonically as the particle size increases and almost no fish-hook effect appears. As the air amount increases, the fish-hook effect of the higher density becomes more distinctness, and classification efficiency of fine particle decreases more significantly.

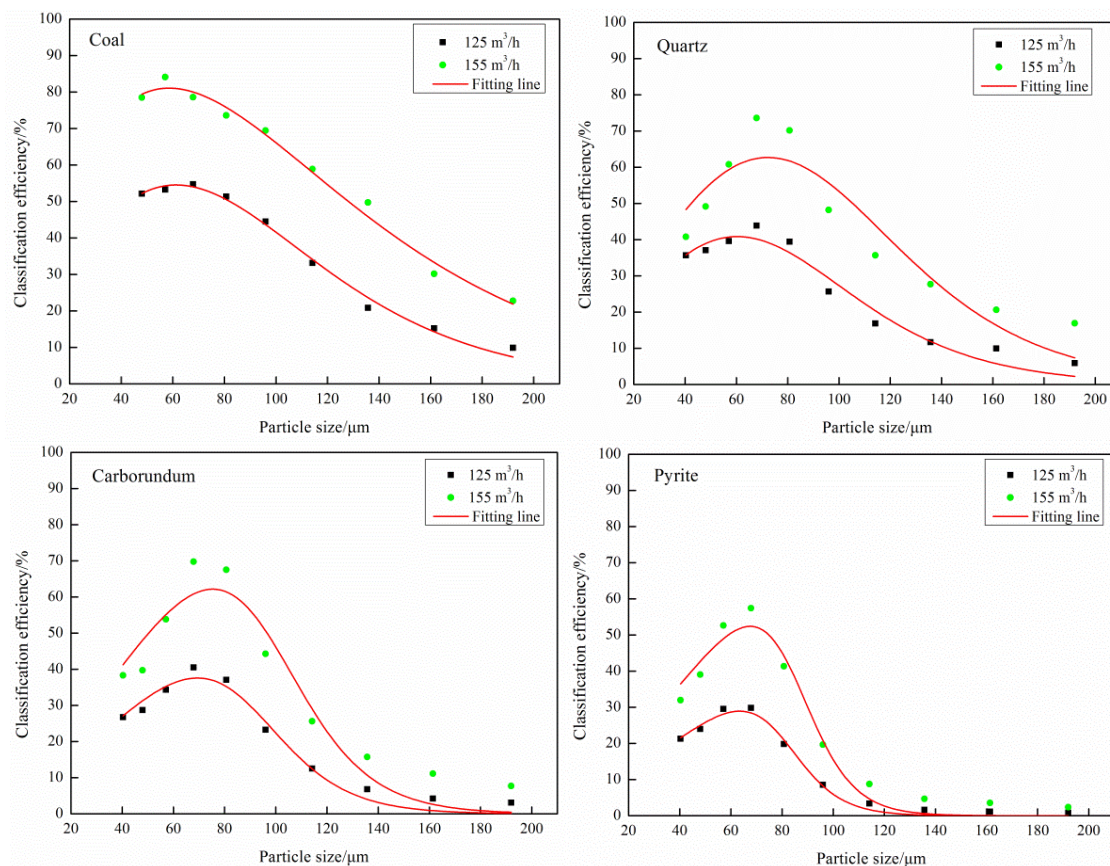


Fig. 7. Fitting curves of classification efficiency

The Whiten’s model is applied to fit the classification efficiency curves of each material and results are shown in Table 2.

$$E_{oai} = \underbrace{[(1 + \beta\beta^* d_i / d_{50c})]}_1 \underbrace{(\exp(\alpha) - 1)}_2 / \underbrace{[\exp(\alpha\beta^* d_i / d_{50c}) + \exp(\alpha) - 2]}_3 \tag{3}$$

where  $a$  is the sharpness of separation,  $d_{50c}$  is the corrected cut size,  $\beta$  is the parameter that controls the initial decrease of the curve in fine sizes (fish-hook effect),  $\beta^*$  is the parameter that preserves the definition of  $d_{50c}$ . When  $d=d_{50c}$ ,  $E=1/2C$ .

### 3.4. Modification of classification efficiency model

The classical Whiten’s model can describe the classification efficiency of particles with homogeneous density. And the above results show that the classification efficiency of particles is the result of both particle size and density. In order to improve the prediction reliability of the classification efficiency model, the density parameter should be introduced in the model.

In the Whiten’s model, the first term controls the stage of fishhook effect, where size has positive correlation with the classification efficiency. The second term is only related to the sharpness of separation. And the third term is mainly related to the whole stage except fishhook effect, where size has negative correlation with the classification efficiency. While for particles with all fractions, classification efficiency decreases as density increases. Thus, density parameter with various forms is introduced in the Whiten’s model, and presented as followed:

$$E_{oai} = (1 + \lambda_1 d_i / \rho) [\exp(\alpha' \rho) - 1] / [\exp(\lambda_2 d_i \rho) + \exp(\alpha' \rho) - 2] \tag{4}$$

where  $\rho$  is the density of material to be separated,  $\lambda_1$  and  $\lambda_2$  are parameters,  $\lambda_1 = \beta\beta^*/d_{50c}$ ,  $\lambda_2 = a\beta^*/d_{50c}$ , and  $a'$  is sharpness of separation.

The improved classification efficiency model is used to describe the test results. The fitting results are shown in Table 3.

Thus, classification efficiency models at 125 m<sup>3</sup>/h and 155 m<sup>3</sup>/h air amounts are:  
125 m<sup>3</sup>/h air amount:

$$E_{oai} = (1 + 1.92d_i / \rho) [\exp(2.14\rho) - 1] / [\exp(0.025d_i \rho) + \exp(2.14\rho) - 2] \tag{5}$$

155 m<sup>3</sup>/h air amount:

$$E_{oai} = (1 + 2.76d_i / \rho) [\exp(2.01\rho) - 1] / [\exp(0.021d_i \rho) + \exp(2.01\rho) - 2] \tag{6}$$

The correlation coefficients of fitting results are 0.96 and 0.89, respectively, which indicates that the improved classification efficiency model with introducing the material density parameter, can explain the combined influence of particle size and density on the classification efficiency. The new Whiten’s model improves the adaptability of the primary one and could obviously reveal the difference in classification efficiency of multi-component particles within classifier.

For further verification the accuracy of model, the density of coal, quartz, carborundum and pyrite are put into formula and the classification efficiency curves of each pure mineral can be calculated and compared with the experimental data. The fitting results are listed in Table 4 and illustrated in Fig.8.

Table 3. Fitting results of parameters applying improved model

Air amount /(m <sup>3</sup> /h)	parameters			R <sup>2</sup>
	a'	λ <sub>1</sub>	λ <sub>2</sub>	
125	2.14	1.92	0.025	0.96
155	2.01	2.76	0.021	0.89

As can be seen from Table 5 and Fig. 8, the fitted curve matches well with the corresponding classification test data, and the classification efficiency of different density minerals can be described more accurately. But the applicability of this new model still needs to be discussed in more detail and further verified.



Table 4. The goodness of fit between calculation and experimental result of classification efficiency

Air amount /(m <sup>3</sup> /h)	Materials	Density /(g/cm <sup>3</sup> )	Parameters			R <sup>2</sup>
			$\alpha'$	$\lambda_1$	$\lambda_2$	
125	Coal	1.25	2.14	1.92	0.025	0.95
	Quartz	2.60				0.96
	Carborundum	3.20				0.99
	Pyrite	4.60				0.97
155	Coal	1.25	2.01	2.76	0.021	0.88
	Quartz	2.60				0.86
	Carborundum	3.20				0.90
	Pyrite	4.60				0.92

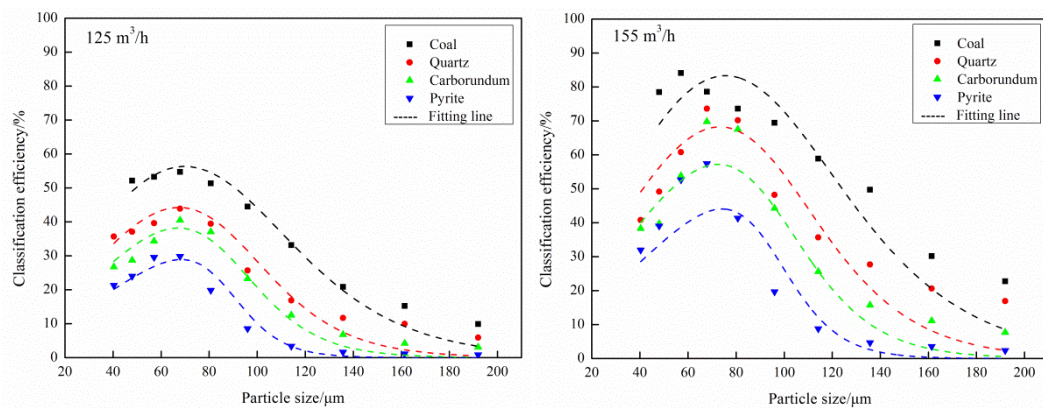


Fig. 8. Fitting curves of classification efficiency applying improved model

#### 4. Conclusions

The study mainly focuses to compare the classification efficiency of particles with different density within a lab-scale static classifier. From the analysis of surface response methodology to the narrowed size experiments, it can be concluded that particle density is another significant influence factor of overflow yield, besides particle size and air amount. Wide size classifications of coal, quartz, carborundum and pyrite indicate that change of material density would change the cut size, sharpness of classification and fishhook parameter, which results in various classification curves. An improved classification efficiency model with introducing the material density parameter into the Whiten's model is established:

$$E_{oi} = (1 + \lambda_1 d_i / \rho) [\exp(\alpha' \rho) - 1] / [\exp(\lambda_2 d_i \rho) + \exp(\alpha' \rho) - 2] \quad (7)$$

Besides, verifications are conducted on the classification results at 125 and 155 m<sup>3</sup>/h air amounts, respectively, which proved that improved model can explain the combined effect of particle size and density on the classification efficiency.

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