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Response of energy-size reduction to the control of circulating load in vertical spindle pulverizer

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Abstract: In the vertical spindle pulverizer (VSP), the large circulation ratio and high ash and sulfur contents in circulating load would result in intensive energy consumption and low grinding efficiency. Although the control of circulating load would help increase the energy efficiency, no quantitative study has been conducted due to the high temperature and pressure in the closed VSP. In this study, response of energy-size reduction to the control of circulating load was studied by the experimental simulation method. Coal mixtures with fine/coarse ratio of 11:1, 8:1 and 6:1 were ground by a lab-scale roller mill. Energy-size reductions of the coarse coal were compared to evaluate the influence of circulating load control. Results showed that the product with the coarse coal increased by 30% when the specific breakage energy was 1.0 $kW \cdot h \cdot t^{-1}$ as the circulation ratio decreased from 11 to 6. Meanwhile, a breakage characteristic index of the coarse coal was two times higher due to the cushioning effect of fines. Besides, decrease of circulation ratio led to increase of the breakage rate of coarse coal, and the energy saving improved by 57%. With the same energy input of 2.0 $kW \cdot h \cdot t^{-1}$, the yield of –0.09 mm pulverized fuel (PF) increased from 22 to 43%. Therefore, controlling the circulating load is an effective method to improve the breakage rate of coarse coal and energy efficiency for PF generation.

Keywords: *circulating load control, response of energy-size reduction, mixture grinding; energy efficiency*

Introduction

In coal-fired power plants, a pulverization process is extremely energy intensive, approximately consuming 0.5–1% of gross power generation (Wei et al., 2013). A small gain in the comminution efficiency would make a significant impact on the operating costs of a plant as well as on conserving resources. The vertical spindle pulverizer (VSP), with an air classifier installed above the grinding table, is widely

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used for yielding the pulverized fuel (PF). Operation process of VSP is shown in Fig. 1 (Xie et al., 2015a). Coal is ground by rollers and entrained by upward swirling air to an elutriation zone. Larger particles fall down to a grinding bed, while smaller ones are directed to a classifier. Through a secondary classification under the joint action of centrifugal force and gravity, standard PF follows the hot air out through the outlets and into the burner, while other particles fall back for regrinding. Shi and He (2011) researched the operation situation of the industrial VSP by online sampling. Experimental data indicated that the calculated circulation ratio varied between 8 and 12 in the fully closed milling-classification system (Zuo, 2013). Also, an interesting result showed that ash and sulfur contents in particles on the grinding table were much higher than those of the fresh feed, respectively. This was because comminution materials not only came from the new feed, but also consisted of retained particles, rejects of elutriator and classifier. Thus, researches on the characterization of grinding behavior and energy consumption in the VSP would be complex since the comminution material is heterogeneous and in a wide size distribution. Shi (2014a, b) and (Shi and Zuo, 2014) developed a series of multi-component models of comminution in relation to the energy input, particle size and density. Based on the industrial data, a mechanistic breakage model incorporated the coal specific properties and machine specific variables was also developed (Shi et al., 2015; Kojovic et al., 2015). On the other hand, to control the circulating load in high ash and sulfur contents, the feasibility of pyrite removal from the circulating load before being reground by applying a dilute phase gas-solid fluidized bed was investigated (Wang, 2013; Wang et al., 2013a, b). In this way, both removal of the hard to grind material and reduction of the circulating load were achieved. However, responses of energy consumption and particle breakage behavior to the control of circulating load have not been discussed.

As materials on the grinding table of VSP come from several parts, it would be a heterogeneous grinding with coals in multi-size fractions. Note that the mixture grinding of particles in different sizes was of interest by some researchers (Austin et al., 1981; Woodburn et al., 1987; Celik, 1988; Verma et al., 1995; Fuerstenau et al., 2010), but the experiments were mainly conducted on pure materials by applying ball mills. Besides, much attention was paid to the energy split phenomena of components in the heterogeneous grinding (Fuerstenau et al., 1991, 2011). In comparison with the heterogeneous grinding in VSP, the breakage mechanism and material property were different. Thus, these conclusions may not be suitable.

Controlling the circulating load would affect the reduction of ash and sulfur content, as well as the circulation ratio. Hence, in this paper fine particles of various ash and sulfur content were utilized to represent the circulating load with different preparation degrees. Mixtures of coarse and fine particles in different mass ratios were prepared to study the breakage process of materials on the grinding table of VSP. All grinding experiments were carried out in identifying experimental conditions. Note that discussions of results were conducted based upon two assumptions. The size distribution of fine particles in three groups was presumed to be the same. The other is ignoring the effect of adding coarse coal on the energy consumption and grinding behavior of fine coal. Breakage kinetics and energetics of the coarse coal were revealed to demonstrate the impact of circulating load control.

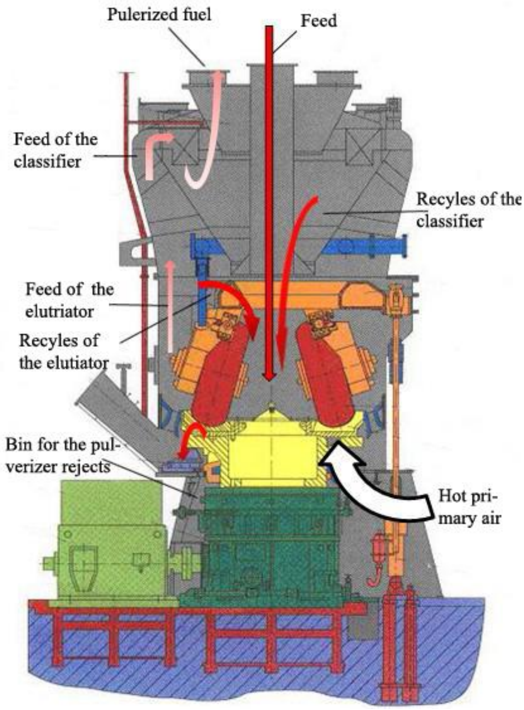

Fig. 1. Operation process of vertical spindle pulverizer

Materials and methods

A self-manufactured roller mill was applied to conduct simulation experiments on the breakage process of particles (Xie et al., 2015a). A 120 g sample of experimental material was used in each grinding test. The coarse coal was in a narrow size fraction of -5.6+4 mm, and the size distribution of fine coal referred to that of the circulating load, which was obtained from sampling data on the industrial VSP (Shi and He, 2011; Wei et al., 2013). The mass fractions of fine coal in the size of -0.5+0.2, -0.2+0.09 and -0.09 mm were 20, 50 and 30%, respectively. Three groups of fine coal, with ash contents of 30, 45 and 60%, and with sulfur contents of 1, 5.23 and 9.09%, were mixed with coarse coal at mass ratios of 6:1, 8:1 and 11:1, respectively. The grinding periods for mixtures were settled to be 10, 20, 30, 40, 50, 60, 90 and 120 s. For comparison and evaluation purposes, three groups of fine coal were ground separately before conducting mixed grinding experiments for the same interval. All the ground products were sieved for 5 min using a vibrating sieving shaker comprising wire mesh sieves of 0.5, 0.25 and 0.09 mm. Then, each over size proportion was screened for another 5 min and coal mass of each size fraction was weighed.

As mentioned above, the effect of adding coarse coal on the breakage of fines was assumed to be negligible. Thus, grinding behavior of the coarse coal in mixtures, such as the energy consumption and size distribution of progenies, was evaluated by comparison with the corresponding item in the single grinding of fine coal.

Results and discussion

Energy consumption of the coarse coal

Generally, energy input of a roller mill during grinding processing is calculated by the following equation (Xie et al., 2015b):

$$\mathrm{E} = \int_0^t (p) dt = \int_0^t (F \cdot f \cdot r \cdot n_b)\, dt \tag{1}$$

where E is the energy input of the mill (J), p is the power draw(J·s^{-1}), F is the roller loading force (N), f is the sliding friction coefficient, r is the radius of rotation (m), n_b is the number of roller.

In single and mixed grinding experiments, operation parameters of mill, roller loading force, rotational radius and roller number, were kept constant. Therefore, the energy input was mainly affected by the friction coefficient. Energy consumptions of the coarse coal in three mixtures at different grinding periods were calculated, and the results are listed in Table 1. It can be seen that at the same grinding period, differences in energy consumption of the coarse coal under three conditions were relatively minor. This was because in single grinding experiments, three groups of fine coal had the same size distributions. As for mixtures, material on the grinding table mainly consisted of fine particles, and about 10–17 g coarse coal, which accounted for 8.33–14.28%, was soon ground into small progenies. Friction coefficients of particles on the grinding table were alike in each single grinding test, so they were in each mixed grinding test, resulting in a similar value of energy inputs. Table 1 obviously presented that energy applied for the coarse coal breakage was approximately equal at different circulation ratio. However taking into consideration the mass of coarse coal, significant differences were found in the specific breakage energy (Fig. 2). The highest circulation ratio at 11:1 kept the highest specific breakage energy, while the circulation ratio of 6:1 had the lowest value.

Based on progeny size distribution curves, product with the coarse coal t_{10} was calculated, and variations of t_{10} with grinding time in different mixtures are shown in Fig. 3. At the same grinding period, t_{10} increased with the increase of the content of coarse coal in the mixture. Meanwhile, in a short period of time (20-60 s), differences in t_{10} slowly grew to the maximum at 60 s, and then gradually decreased and vanished as the grinding period further extended. Reasons for the difference in t_{10} would be further analyzed combined with energy in the next section. After being ground for about 90 s, the size of most progenies was finer than 0.5 mm, which was finer than the corresponding characteristic size (0.47 mm) of t_{10} for the coarse coal (-5.6+4 mm).

Table 1. Changes of energy consumption with grinding period for the coarse coal

Grinding period, s	Energy input, J		
	6:1	8:1	11:1
20	28.99	26.62	26.68
30	38.09	39.75	39.88
40	52.66	49.94	50.88
60	76.35	71.69	73.9
90	107.27	103.89	108.11
120	133.87	134.75	141.31

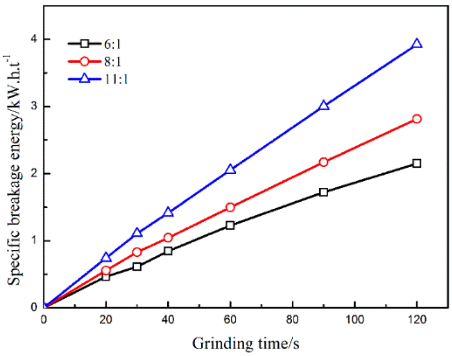

Fig. 2. Specific breakage energy varies with grinding period in three mixtures

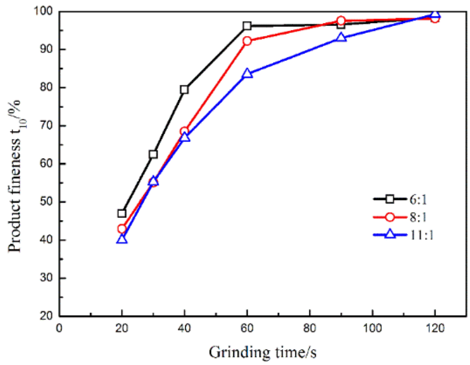

Fig. 3. Change of fineness t_{10} with grinding period in each mixing ratios

Relationship between energy and size reduction of coarse coal

Differences in the size distribution of either progenies or fineness t_{10} are attributed to differences in the grinding energy efficiency of three mixtures. Figure 4 describes the relationship between t_{10} and specific breakage energy at each mixing ratios. At the same specific breakage energy, 6:1 mixture has the highest t_{10}, while 11:1 mixture has the lowest one. More specifically, when the specific breakage energy is 1.0 kW·h·t^{-1}, the product fineness t_{10} of circulation ratio as 6:1 and 8:1 is higher than that of 11:1 by 15% and 30%, respectively. In other words, the lowest grinding energy efficiency occurs at a fine-to-coarse ratio of 11:1, though coarse coal obtains the highest specific breakage energy.

The breakage equation, which is used to describe the relationship between specific energy and product t_{10}, originates from a drop weight tester (DWT). Later, this model helps to develop the energy-size reduction process of materials in the Hardgrove mill

(Napier-Munn et al., 1996) and roller mill (Xie et al., 2015a). In this paper, aiming to further analyze the effect of circulating load control on the breakage characteristics of the coarse coal, experimental data are fitted by applying classic energy-size model (Shi and Kojovic, 2007):

$$t_{10} = A \times \left(1 - e^{-b \cdot E_{cs}}\right) \tag{2}$$

where t_{10} is the cumulative percentage of the broken particles smaller than one tenth of the geometric mean size of the feed particles (%), A and b are ore-dependent parameters, E_{cs} is the specific breakage energy (kW·h·t^{-1}).

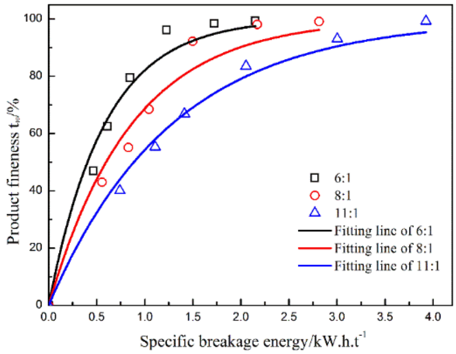

Fig. 4. Relationship between fineness t_{10} and specific energy in each mixing ratios

The fitted results of A and b are listed in Table 2. Note that A means the maximum value of t_{10} which could be obtained in breakage. If the fitted A value is bigger than 100, it should be set as 100 and b value is refitted. Value of $A \cdot b$ is applied as an indicator of ore resistance to breakage. A higher $A \cdot b$ normally indicates a diminished resistance to breakage.

Table 2. Fitting parameters for each breakage condition

Breakage conditions	Parameters			
	A	b	$A \cdot b$	R^2
6:1	100	1.7177	171.77	0.9792
8:1	100	1.1605	116.05	0.9729
11:1	100	0.7822	78.22	0.9920

When mass ratio of fine-to-coarse coal varies from 6:1 to 11:1, the comparison shows that $A \cdot b$ value decreases from 171.77 to 78.22, by 54.46%. It clearly indicates that the breakage behavior of coarse coal would change significantly in different breakage environments. If materials on the grinding table consist of less coarse coal and more fine particles, a softer bed would be formed and show much evident cushioning effect. Bed volume shrinks under extrusion, and breakage energy acting on the coarse coal is gradually distracted by fine particles, which results in relative lower energy efficiency. Eventually the coarse coal would represent higher resistance ability to breakage.

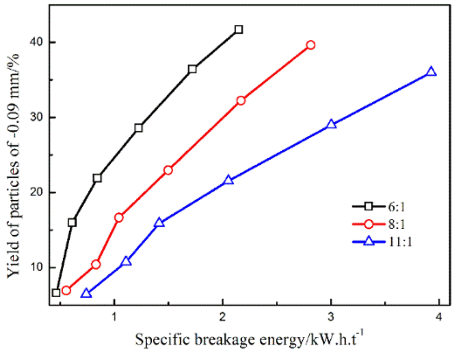

Fig. 5. Relationship between yield of fines in –0.09 mm and specific energy for each mixing ratio

In a coal fired power plant, coal particles finer than 0.09 mm are regarded as qualified PF. Therefore, 0.09 mm is an important characteristic size. As mentioned above, the corresponding characteristic size for t_{10} of coarse coal progeny reaches to 0.47 mm, and fineness t_{10} approaches to 100% after being ground for 120 s. Thus, in order to analyze the impact of circulating load control on PF generation from a better simulation and comparison perspective, this paper also investigates the relationship between the generation of –0.09 mm PF and the specific breakage energy, and results are illustrated in Fig. 5. Compared with Fig. 4, differences in the energy efficiency are more evident among the three mixing ratios. When the circulation ratio decreases from 11 to 6 at the specific breakage energy of 2 kW·h·t^{-1}, the yield of -0.09 mm PF increases from 22 to 43%. When the yield of -0.09 mm PF reaches up to 30%, the required specific breakage energy for coarse coal grinding decreases from 3.0 to 1.3 kW·h·t^{-1}, and more than 50% energy is saved.

Conclusions

As the control of circulating load has an essential effect on the improvement of the energy efficiency in the VSP, it is necessary to quantitatively evaluate the following response of energy-size reduction of coarse coal. By simulation researches, this paper compared the energy consumption, fineness progenies and breakage rate of the coarse coal in the mixtures at fine-to-coarse ratio as 6:1, 8:1 and 11:1. Thus, the effects of the circulating load control on energy efficiency were preliminarily concluded. The energy that applied for coarse coal breakage is approximately equal for the three circulation ratios. However, if the circulation ratio decreases from 11 to 6, the breakage characteristic index of coal sample, $A{\cdot}b$, will increase more than 2-fold, and energy output would reduce by 56.67%. With the same specific breakage energy, the yield of -0.09 mm pulverized fuel would increase twice. Even though there were some differences in grinding of particles in simulation research and in industrial VSP on the circulating load control, experiment results still indicated that the breakage rate of coarse coal and energy efficiency of pulverized fuel generation could be effectively improved by the control of circulating load.

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References

AUSTIN L.G., BAGGA P., 1981. *An analysis of fine dry grinding in ball mills*, Powder Technol., 28, 83-90.

CELIK M.S., 1988. *Acceleration of breakage rates of anthracite during grinding in a ball mill*, Powder Technol., 54, 227-233.

FUERSTENAU D.W., ABOUZEID A.Z.M., 1991. *Effect of fine particles on the kinetics and energetics of grinding coarse particles*, Int. J. Miner. Process, 31, 151-162.

FUERSTENAU D.W., ABOUZEID A.Z.M., PHATAK P.B., 2010. *Effect of particulate environment on the kinetics and energetics of dry ball milling*, Int. J. Miner. Process, 97, 52-58.

FUERSTENAU D.W., PHATAK P.B., KAPUR P.C., ABOUZEID A.Z.M., 2011. *Simulation of the grinding of coarse/fine (heterogeneous) systems in a ball mill*, Int. J. Miner. Process, 99, 32-38.

KOJOVIC T., SHI F., BRENNAN M., 2015. *Modelling of vertical spindle mills. Part 2: Integrated models for E-mill, MPS and CKP mills*, Fuel, 143, 602-611.

NAPIER-MUNN T.J., MORRELL S., MORRISON R.D., KOJOVIC T., 1996. *Mineral comminution circuits: their operation and optimisation*. ISBN 064628861x. Julius Kruttschnitt Mineral Research Centre, Chapter 4.

SHI F., 2014a. *Coal breakage characterization-Part 2: Multi-component breakage modeling*, Fuel, 117, 1156-1162.

SHI F., 2014b. *Coal breakage characterisation-Part 3: Applications of the multi-component model for HGI prediction and breakage simulations,* Fuel, 117, 1163-1169.

SHI F., HE Y.Q., 2011, April. *Efficiency improvements in coal fired utilities, Asia-Pacific Partnership on Clean Development and Climate*. Julius Kruttschnitt Mineral Research Centre and China University of Mining & Technology.

SHI F., KOJOVIC T., 2007. *Validation of a model for impact breakage incorporating particle size effect,* Int. J. Miner. Process, 82, 156-163.

SHI, F., KOJOVIC, T., BRENNAN, M., 2015. *Modelling of vertical spindle mills. Part 1: Sub-models for comminution and classification*, Fuel, 143, 595-601.

SHI F., ZUO W.R., 2014. *Coal breakage characterization-Part 1: Breakage testing with the JKFBC,* Fuel, 117, 1148-1155.

VERMA R., RAJAMANI R.K., 1995. *Environment-dependent breakage rates in ball milling*, Powder Technol., 84, 127-137.

WANG S., 2013. *Particle separation behavior of recirculating load of power station pulverizer in the dilute phase vibrated gas-solid fluidized bed*, PhD Thesis, Xuzhou: China University of Mining and Technology.

WANG S., HE Y.Q., HE J.F., GE L.H., LIU Q., 2013a. *Experiment and simulation on the pyrite removal from the recirculating load of pulverizer with a dilute phase gas-solid fluidized bed*, Inter. J. Min. Sci. Technol., 23, 301-305.

WANG S., HE Y.Q., WANG H.F., HE J.F., CAI B., 2013b. *Study on recirculating loads of power plant pulverizer separated by dilute gas-solid fluidized bed*, J. China Coal Soc, 38(3), 480-486. (In Chinese)

WEI H., HE Y.Q., SHI F.N., ZHOU N.X., WANG S., GE L.H., 2014. *Breakage and separation mechanism of ZGM coal mill based on parameters optimization model*, Inter. J. Min. Sci. Technol., 24, 285-289.

WOODBURN E.T., KALLIGERIS S.A., 1987. *The investigation of the kinetics of breakage as a first step towards the assessment of the economics of ultra-Fine grinding of a British low-rank coal*, Powder Technol, 53,137-143.

XIE W.N., HE Y.Q., LUO C., ZHANG X., LI H., WANG H.F., SHI F.N., 2015b. *Energy-Size Reduction of Coals in the Hardgrove Machine*, Inter. J. Coal Prep. Util., 35(2), 51-62.

XIE W.N., HE Y.Q., ZHANG Y.H., HUANG Y., LI H., WEI H., WANG H.F., 2015a. *Simulation study of the energy-size reduction of MPS vertical spindle pulverizer*, Fuel, 139, 180-189.

ZUO W., 2013. *Mathematic modeling and optimization on the process of MPS coal mill*, PhD Thesis, Xuzhou: China University of Mining and Technology.