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Calculation model of coal comminution energy consumption

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ABSTRACT

Experiments on comminution energy of different coals under conditions for CFB (circulating fluidized bed) boilers were carried out in a jaw crusher and a parallel roller crusher. The R–R (Rosin–Rammler) distribution was used to describe the size distribution of the crushing product. The size distribution of the product has a significant influence on comminution energy. With lower values of $x_{P=63.2\%}$ (size modulus) or α (distribution modulus), the comminution energy increases. With a fixed particle size distribution of the product, the comminution energy increases gradually with the increasing of feed coal size, while, when the feed coal size is larger than 15 mm, the effect can be neglected. With a fixed outlet width of the crusher, the average product size tends to be finer when smaller sized particles or coal with higher HGI (Hardgrove grindability index) are fed into the crusher. Therefore, in coal preparation process, the adjustment of the crusher should be performed considering coal grindability or crushability and the feed coal size distribution. At last, an empirical model of comminution energy was proposed and validated by the measured values with ±25% of accuracy.

1. Introduction

According to flow patterns reconstruction proposed by Tsinghua University, the circulating fluidized bed (CFB) boilers (Li et al., 2009, 2013; Hu et al., 2009) can be operated under relatively low pressure drop across the furnace, by controlling the size distribution of coal particles fed to the boiler (Yang et al., 2009; Liu et al., 2015). With lower furnace pressure drop, the power consumption of air fans can be reduced, whereas the comminution energy consumption of coal particles will be increased. To optimize the auxiliary power consumption, the balance point between the power consumption of air fans and that of the coal comminution should be investigated.

Comminution is a fundamental operation in mineral processing and expends significant amounts of energy (Desmond, 2008). For more than one hundred years, a large interest has been focused on the energy-size reduction relationships, in which laws of Rittinger, Kick and Bond are notable (Rittinger, 1867; Kick, 1885; Bond, 1952). They can be expressed in an equation proposed by Walker et al. (1937)

$$\mathrm{d}e = -C\frac{\mathrm{d}x}{x^n} \quad (1)$$

where e is the energy consumption, x is the particle size, C and n are constants. The specific values of n as 2, 1 and 1.5 correspond to Rittinger's, Kick's and Bond's laws respectively.

Hukki (1961) proposed that the index n in the above equation should be influenced by the particle size. Then Voller (1983) assumed the expression of $n(x)$ as follows

$$n(x) = 2 + \frac{\log C}{\log x} - \frac{\log(ax+b)}{\log x} \quad (2)$$

With this assumption, the energy-size relationship can be described as the superposition of Kick's and Rittinger's Laws.

$$\mathrm{d}e = -a\frac{\mathrm{d}x}{x} - b\frac{\mathrm{d}x}{x^2} \quad (3)$$

Hiorns (1970), Rebinder and Chodakow (1962) and Holmes (1957) improved these models by considering more factors, such as the friction between particles, surface energy and non-uniformity of brittle materials. As the above models just consider the single size particles, Charles (1957) developed his model by introducing the size distribution to Walker's method.

$$e = \int_{x}^{x_{\max}} \int_{x_1}^{x} \left(-C\frac{\mathrm{d}x}{x^n}\right)\mathrm{d}P \quad (4)$$

in which P is the size distribution of the product, $x_{\max}$ is the size of the largest fragment and x_1 is the feed size. Stamboliadis (1996, 2000, 2002) further expanded its application by introducing the

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Nomenclature

e	comminution energy consumption	$x_{P=63.2\%}$	size modulus
x	particle size	D_f	fractal dimension
n	size index	$x_{\min}$	minimum size
C	comminution energy coefficient	e_x	specific energy of a single particle
a	constant	e_∞	specific energy of a particle of infinite size
b	constant	e_p	potential energy of the product particle assembly
$x_{\max}$	maximum size	e_f	potential energy of the feed particle assembly
x_f	feed size	x_{fi}	size group of feed particles
$x_{1(80)}$	80% passing size of the feed coal	$f(i)$	mass fraction of particles with size x_{fi}
$x_{2(80)}$	80% passing size of the product	HGI	Hardgrove grindability index
M_i	constant	m	mass of product particles finer than 0.071 mm
K	constant	x_{pi}	size group of product particles
P_x	cumulative mass of particles smaller than x		
α	distribution modulus		

Gaudin–Schuhmann (G–S) distribution and analyzing the relationship between the distribution modulus α and the constant n.

Morrell (2004a, 2004b, 2008, 2009, 2010) and Bond and Wang (1950) developed an empirical model by correlating the comminution energy with 80% passing size of the feed coal and the product, which was based on the Bond's law.

$$e = M_i K\left(x_{2(80)}^{n(x_2)} - x_{1(80)}^{n(x_1)}\right) \tag{5}$$

where M_i and K are constants, $x_{1(80)}$ and $x_{2(80)}$ are the 80% passing size of the feed coal and the product respectively.

$$n(x_i) = -\left(0.295 + \frac{x_i}{1000000}\right) \tag{6}$$

Recently, new theories and mechanics have been proposed to explain the complex changes in the comminution process. Thomas and Filippov (1999) suggested a structural fractal model and correlated the energy consumption during breakage with the fractal dimension. The model lies on a basic assumption that the fragmentation conditions of material depend on its genuine structure of the architecture and of the shape of natural discontinuities. Carpinteri and Pugno (2003) developed the fractal model and proposed a multifractal comminution approach for drilling with a non-constant fractal exponent. Englman et al. (1988) described the size-distribution with entropy maximization and Nadolski et al. (2014) proposed an energy benchmarking model for mineral comminution.

The calculation models and experimental data on energy-size relationship available in the literature are mostly limited to rock or other ores, or coal grinding with finer particle size (Fuerstenau and Kapur, 1995; Khumalo et al., 2007; Shi et al., 2003; Refahi et al., 2010; Ballantyne and Powell, 2014; Wheeldon et al., 2015). In order to develop reliable coal comminution energy models for CFB boiler conditions, it is necessary to obtain energy consumption data for coal particles with relative coarse and wide size distribution. Thus, the aim of the present work is to provide experimental data and develop a calculation model on the energy-size relationship of coal crushing.

2. Experiments

2.1. Crushers

Experiments have been performed in two lab-scale crushers: a jaw crusher (a jaw plate oscillating) and a parallel roller crusher (two rollers with smooth surface rotating in the opposite direction), commonly used for coal preparation in CFB power plants. Both of the crushers achieve material breakage through extrusion between the main parts. For different size ranges of the feed particles, the outlet widths of the jaw crusher and the parallel roller crusher were adjusted as 3, 4, 6, 9 mm and 0.5, 1, 1.5 mm, respectively. The coal particles fed into the CFB boilers are usually in the size range of 0–8 mm, covered by the product size in the tests. The sample mass for the jaw crusher was 2 kg and the parallel roller crusher 0.5 kg. The other parameters of the crushers are listed in Table 1.

2.2. Feed coal particles

Crushing and grinding focus on different size stages in comminution processing, crushing for coarse particles and grinding for fine particles. Crushability or grindability of coal refers to the difficult degree of comminution, namely the energy expended in comminution. The Hardgrove grindability index (HGI) is a common method to describe the grindability. It can be determined through a HGI measuring instrument. With a certain amount of energy input, the finer the product is, the higher HGI is. It means that for the same size reduction, coal with higher HGI requires less comminution energy. There are a number of limitations associated with HGI, such as mimicking continuous coal pulverization by batch processing and highly non-linear nature of the HGI values (Shi and Zuo, 2014; Shi, 2014a, 2014b). Despite its limitations, it has gained wide application in the past. For coal utilization, the HGI is a very important index and used as a specification in many commercial contracts (Shi and Zuo, 2014). In this work, it was used to describe the coal resistance to breakage. Four coal types with different grindability were used for the comminution experiments. The HGI and proximate analysis for four coals are listed in Table 2.

For determination of coefficients in the calculation model, coal particles were sieved into a narrow size range and then fed into the crushers. Coal particles with a wide size range were also crushed for validation of the model. The parameters in each test are listed in details in Table 3.

Table 1
Parameters of the crushers.

Crushers	Feed inlet size (mm)	Feed coal size (mm)	Product size (mm)	Rated power (kW)
Jaw crusher	100 × 125	<80	3–15	3.0
Parallel roller crusher	–	⩽13	0–3	1.5