The Development of a Ring Ball Mill Simulation Model†

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Abstract

The mathematical model previously developed for a ring ball mill based on specific rates of breakage, breakage distributions, and primary and secondary classification actions was further refined. In particular, empirical expressions are presented for both primary and secondary classification actions as a function of the mill and classifier geometry as well as the operating conditions. In addition, the scale-up factor with the make-up feed rate determined in a pilot-scale mill was further developed for larger mills. Model simulations based on parameters measured in the Hardgrove mill with the present classification models and scale-up factors correctly predicted the circuit behavior of industrial-scale mill systems.

Furthermore, some of the factors affecting the mill performance were investigated with the present simulation model. As a result, the feed size distribution and the total crushing load on balls were found to be the dominant factors.

1. Introduction

Roller mills are widely used to prepared pulverized coal for firing in boiler furnaces and are classified into ring roll mills and ring ball mills according to the shape of the roller1). The mode of operation of the roller mills depends on that of the boilers, which is different from normal applications of grinding mills where the rate of grinding is usually kept constant. The coal pulverizers are operated mainly on the basis of experience accumulated over many years.

Recent trends in Japanese utility boilers have moved from homogeneous coals to the burning of a variety of imported coals and to the operation of the boiler at various loads with rapid changes. Therefore, advanced coal grinding technology is required to cope with these boiler requirements. To satisfy these new demands, the behavior of roller milling circuits must be quantitatively described.

Over the last two decades, the theory of grinding has been developed based on descriptions of the breakage process, the flow and mixing through the mill, and the classifier behavior all of which are similar to those in chemical reactor theory2). In a roller mill system, Murata et al.3) analyzed the pressure exerted in the particle layers between the roller and the grinding table, and they concluded that the roller design is a key factor in the optimization of the roller mill circuit. On the other hand, Austin et al.4~6) constructed a mathematical model for a ring ball mill system based on specific rates of breakage and primary fragment distribution. They obtained breakage parameters in the Hardgrove grindability machine7) which is a batch ring ball mill. They measured classification parameters in a pilot-scale mill (D = 430 mm) and then determined scale-up factors from the batch mill to the pilot plant mill using a simulation model.

The model gave valuable insights into the mode of operation of the ring ball mill, and it
enabled predictions of the effect of operating variables to be made. However, the applicabil­
ity of the model to mills other than the pilot mill is questionable because they evaluated
the classification characteristics within limited tests conducted in a pilot-scale mill and did not
refer to the scale-up effect of the classifiers.

In this paper, improvements were made to the model developed by Austin et al., by in­
corporating scale-up rules for grinding and classification actions which were determined
by the analysis of laboratory tests and operating data of industrial-scale mills describing the
behavior of this type of mill. The validity of the modified model was verified by operating data
from industrial-scale mills. Furthermore, the effect of operating conditions on pulverized-coal fineness was studied by model simulations.

2. Modeling of ring ball mills

2.1 Air-swept ring ball mills

Figure 1 shows an industrial ring ball mill and the flow patterns of various coals, and the
air in the mill is shown in Fig. 2. Raw coal enters the center of the rotating table through
a central coal inlet chute. The coal on the table is thrown to the area surrounding the table by
centrifugal action. The coal is pulverized when going through heavily loaded grinding balls and
then it is transported to the fluidized bed zone above the throat plate.

Air is supplied through an annular throat plate within the mill, and it sweeps up the pul­
verized coal from the fluidized bed zone. The smaller particles among the materials swept up are conveyed to the inlet of the classifier, and
and the larger particles are separated from the air streams at the air velocity decreases and returns to the rotating table (primary classification). Air and pulverized coal in the classifier form a
swirling stream by classifier vanes, pulverized coals are classified into larger particles and
smaller particles by centrifugal action, and larger particles return to the table to be re­
ground (secondary classification).

2.2 Ring ball mill model

In developing the simulation model of a pilot plant mill, Austin et al. constructed a mill cir­
cuit model of a ring ball mill which is shown in Fig. 3 and derived mass-size balance equations.
The size range is split into \( n \) intervals, and the size intervals which are defined by the \( \sqrt{2} \) screen series are called 1, 2, \( \cdots \), \( i-1 \), \( i \), \( i+1 \), \( \cdots \) \( n \) from the largest size interval. That is, if the upper size of interval \( i \) is \( x_i \), the lower size of interval \( i \); \( x_{i+1} \) is equal to \( \sqrt{2} \) \( x_i \). If the grinding zone is fully mixed, the mass balance on material of size \( i \) at the grinding zone is expressed by the following equation 5,

\[
F'w_i = F'f'i - S_iw_iW + \sum_{j=1}^{i-1} b_{ij}S_jw_jW
\]  

(1)

Next, consider the mass balance at the primary classification zone. \( c'_i \) is defined as the partial separation efficiency of size \( i \) at primary classification. Then Eqs. (2) and (3) are given as;

\[
T'i' = F'w_i c'_i
\]  

(2)

\[
Fp_i = F'w_i(1-c'_i)
\]  

(3)

The ratio of stream \( F \), which is transported from the primary to the secondary classification zone, to stream \( T' \), which is returned to the table, is defined as the circulation ratio of \( C' \). That is, the circulation ratio at the primary classification zone is \( C' = T'/F \). Similarly, the rest of the mass balances involved can easily be derived.

When Eq. (1) is rewritten with the wt. fraction of size \( i \) in the make-up feed which is fed through the coal inlet chute, the following equation is derived 9,

\[
\bar{w}_i = \frac{g_i + (1/F') \sum_{j=1}^{i-1} b_{ij}A_j \bar{w}_j}{(A_i/F') + (1-c'_i)(1-c_i)}
\]  

(4)

where,

\[
A_i = S_iW
\]  

(5)

\[
\bar{w}_i = (1 + C')(1 + C)w_i
\]  

(6)

When the both sides of the Eq. (6) are summed from \( i = 1 \) to \( i = n \), then,

\[
\sum_{i=1}^{n} \bar{w}_i = (1 + C')(1 + C) \sum_{i=1}^{n} w_i
\]

\[= (1 + C')(1 + C)
\]

\[= (1 + \overline{C})
\]  

(7)

where \( \overline{C} \) is the net circulation ratio.

The relationship between through-put \( Q \) and the coal flow rate at the grinding zone i.e. \( F' \) is (see Fig. 3),

\[
Q = \frac{F'}{(1 + C')(1 + C)}
\]  

(8)

The wt. fraction of size \( i \) in mill output i.e. \( q_i \) is given by,

\[
q_i = (1 + C')(1 + C)(1-c'_i)(1-c_i)w_i
\]  

(9)

The circulation ratio at the primary classification zone \( C' \) and that at the secondary classification zone \( C \) are calculated with Eqs. of (10) and (11), respectively.

\[
1 + C' = \frac{1}{\sum_{i=1}^{n} w_i(1-c'_i)}
\]  

(10)

\[
1 + C = (1 + \overline{C}) \sum_{i=1}^{n} w_i(1-c_i)
\]  

(11)

Equation (4) is the mass-size balance which expresses the grinding characteristics of the ring ball mill. This set of equations is readily computed for the given values of \( g_i, A_i, b_{ij}, c'_i, c_i \), and \( F' \), starting with \( i = 1 \).

The value of \( (1 + C')(1 + C) \) is obtained from Eq. (7), and then value of \( w_i \) is gotten from Eq. (6). The value of the wt. fraction of size \( i \) in the mill output \( q_i \) is obtained from Eq. (9), the value of through-put \( Q \) comes from Eq. (8), and the circulation ratios of \( C' \) and \( C \) are obtained from Eqs. (10) and (11), respectively.

2. 3 Method of analysis

In order to solve Eq. (4), it is necessary that
the factors of $A_i$, $b_{ij}$, $c'_i$, $c_i$, and $F'$ be expressed by functions of coal types, mill sizes, mill conditions, and so on.

$A_i$ which has the physical meaning of the rate of breakage of sizes $i$, and $F'$ which is the coal flow rate in the grinding zone, are significantly affected by mill sizes and operating conditions. Furthermore, it is difficult to measure those factors in a large-scale mill.

When $q_i$, $b_{ij}$, $c'_i$ and $c_i$ are given, an identical value of $w_i$ is obtained for a constant value of $A_i/F'$ in Eq. (4), and therefore an identical value of $q_i$ follows.

For the following analysis, therefore, we used the values of the breakage parameters reported by Austin et al.5, and the values of the classification parameters of $c'_i$ and $c_i$ based on the analysis of laboratory tests and on operating data of large-scale mills. Furthermore, with scale-up rules based on the mill dimensions and capacity, the mill performance was investigated by a modified simulation model.

3. Ring ball mill simulation model

3. 1 Breakage parameters

The breakage distribution parameter is one of the parameters which describes size reduction as a rate process. If the cumulative type of this breakage parameter, that is, the fraction of material just broken from the size interval $j$ which appears less than the size interval $i$ is represented by $B_{ij}$, then,

$$B_{ij} = \sum_{k=i}^{n} b_{kj}$$

It is reported5) that the $B_{ij}$ values are normalized with respect to the breaking sizes when the breaking sizes are fairly small in comparison with the grinding ball and furthermore are insensitive to mill size. The $B_{ij}$ values are expressed by the following equation,

$$B_{ij} = \phi (x_{i-1}/x_{j})^\gamma + (1 - \phi) (x_{i-1}/x_{j})^\beta$$

where $\phi$, $\gamma$ and $\beta$ are descriptive parameters for a given coal, and the values measured by Austin et al.5 were used here.

As for specific rates of breakage, Austin et al.5, compared the results of batch tests obtained in the pilot-scale mill with those obtained in the Hardgrove machine. Consequently they reported that $S_i$ passes through the maximum values at a certain size $x_{\text{max}}$ and the $S_i$ values for the smaller sizes can be represented by $S_i = ax_{\text{max}}$. Moreover, the value $a$ is the same for the two mills. The functional form of $S_i = ax_{\text{max}}$ is applied in the region of approximately $x_{\text{max}} \leq 0.1d$. Since in a large-scale mill at the material sizes are in this region, it was assumed that the values of $S_i$ obtained in the Hardgrove machine can be represented by $S_i = ax_{\text{max}}$ for all the particle size ranges. The values of $\alpha$ and $\alpha$, which depend on $H.G.I.$, and measured by Austin et al.5, were used for the analysis.

3. 2 Classification parameters

3. 2. 1 Primary classification efficiency

Factors affecting the classification efficiency were investigated using a two-dimensional model apparatus of the primary classification zone in an industrial mill. The experimental apparatus for primary classification is shown in Fig. 4. The experiments were conducted under the condition of atmospheric temperature and pressure. The larger particles (particle diameter; $2 \sim 10$ mm) which circulate around the primary classification zone, were first charged at the grinding zone. Next, the air flow rate was set at a certain value, and after having the larger particles circulate in the primary classification zone, the smaller particles (weight mean diameter: 0.8 mm) were fed from the coal hopper by means of a rotary valve. Before the particles made one complete circulation around the grinding zone, the air supply and feeding of smaller particles were shut down. The weight and particle size distribution of the feed coal particles and the particles which left the primary classification zone and were recovered at 2 and 3 were then measured, and the partial separation efficiency was obtained from these measurements.
Figure 5 shows an example of the primary classification efficiency. It is clear that the primary classification efficiency is strongly affected by the air flow rate \( A \), and the critical cut size \( x_{50} \) is proportional to \( A \). Thus the partial separation efficiency of size \( i \) at primary classification \( c'_i \) is expressed by the following equation,

\[
c'_i = 0.98 \{ 1 - \exp \left\{ -0.847 \frac{x}{x_{50}}^{2.29} \right\} \}
\]  

(14)

\[
x_{50}^* = k_1 A
\]  

(15)

where \( k_1 \) is depends on mill size.

3.2.2 Secondary classification (classifier performance)

In ring ball mills, cyclone type classifiers have been used. With respect to the classifier performance, the effects of classifier configuration and operating conditions on the grade efficiency of secondary classification were made clear by experiments with a model classifier. Furthermore, scale-up factors were determined by the analysis of the operating data of industrial-scale mills.

The experiments were conducted under the conditions of atmospheric temperature and pressure in the apparatus shown in Fig. 6. After setting the air flow rate, coal particles were fed in for a given time. The larger separated particles in the classifier were collected in a bin which was fitted under the classifier. On the other hand, the smaller particles leaving the model classifier were collected in a filter bag. The weight of both the recovered material and its size distributions were measured, and the partial separation efficiency was then calculated.

An example of the results is shown in Fig. 7, where the performance of the classifier (classifier diameter \( D_e = 380 \) mm) is shown with respect to air velocity at the classifier inlet. The air velocity was varied by adjusting the vane angle which is an angle between the vane and the radius at the pivot. Higher velocities due to the larger vane angle \( \theta \) improves the partial

![Fig. 6 Experimental apparatus for secondary classification](image)

![Fig. 7 Effect of the vane angle on the grade efficiency of secondary classification](image)
separation efficiency $c_i$. However, beyond a certain velocity, the separation efficiency of larger particles decreases. This reduction in efficiency is considered as the re-entrainment of particles which generally occurs in a cyclone separator.

In addition to this, in terms of factors affecting the classifier performance, there are solid loadings at the classifier inlet ($F/A$), outlet skirt length $L$, and so on. For a given geometry of the cyclone type classifier, the partial separation efficiency of size $i$; $c_i$ can be written as follows,

$$c_i = 0.99 \left[ 1 - \exp \left\{ -0.715 \frac{x}{x_{50}}^{1.12} \right\} \right]$$ (16)

$$x_{50} = k_2 \left( \frac{D}{gD_c} \right)^{-0.56} \left( \frac{F}{A} \right)^{0.15} \left( \frac{L}{H} \right)^{0.41} \left( \frac{D_c}{D} \right)^{0.30}$$ (17)

where $k_2$ depends on the classifier configuration. It is noted that the values of the constants on the right hand sides of Eqs. (14) and (16) are 0.98 and 0.99, respectively. This indicates that the separation efficiencies become constant at 0.98 and 0.99, respectively.

3. 3 Scale-up factors

Austin et al. computed Eqs. (4) ~ (11) for a range of $F'$ values with the wt. fraction of size $i$ in the make-up feed $g_i$ used in the pilot-scale mill ($D = 430$ mm) tests, $c_i'$ and $c_i$ measured in the pilot-scale mill, and $A_i$ calculated using the Hardgrove mill until the computed $q_i$ becomes equal to the measured $q_i$ in the pilot plant mill. The mill capacity at the computed $q_i$ value is then treated as the simulated mill capacity $Q_{sim}$ (hypothetical mill capacity in the Hardgrove mill in which separation efficiencies are assumed to be the same as those of a pilot mill). The scale-up factor $k$ is defined as $Q = kQ_{sim}$ with $Q_{sim}$ and the pilot mill capacity $Q$.

Figure 8 shows the relationship obtained by Austin et al. between the scale-up factor $k$ and the mill capacity $Q$. $k$ increases as $Q$ increases, and then it approaches a certain value. If this maximum value $k$ is denoted as $k_m$ and the value of $Q$, at $1/2k_m$ is defined as $Q_n$, the $k$ value for the pilot plant mill is expressed by the following equation,

$$\frac{k}{k_m} = \frac{1}{1 + \left( \frac{Q}{Q_n} \right)^{2.7}}$$ (18)

$$Q_n = k_m S_{16x20}$$ (19)

On the other hand, the absolute rate of breakage of size $i$, $A_i$ is expressed by the following equation,

$$A_i = M \omega D$$ (20)

where $M$ is the total load on the lower grinding ring (hereafter referred to as the crushing load), $\omega$ is the rotational speed of the mill, and $D$ is the mean race diameter. Since $k_m$ is proportional to $A_i$, the value of $k_m$ for industrial-scale mills can be expressed as,

$$k_m = k_0 M \omega D$$ (21)

where $k_0$ is a constant.

4. Studies on the simulation model

4. 1 Verification of the model

The comparison of the simulated and operating capacities and fineness for large-scale mills ($D = 1780$, $D = 2160$ and $D = 3300$ mm) is shown in Fig. 9. The feed size distribution used for the model simulation was the Rosin-Rammler distribution with the distribution modulus of $n = 0.7$ and a top size of 38.1 mm, as shown in Fig. 10.

Although the Hardgrove Grindability Index of coal is different for each large-scale mill as shown in the example of Fig. 9, the simulated values agree well with the operating data. Thus, it is considered that the validity of the modi-
fied simulation model is sufficiently verified.

4. 2 Effect of feed sizes

The effect of feed size distributions on pulverized coal fineness and coal flow rates through the grinding zone were investigated for a coal of 50 H.G.I. which is quite common in grindability. Three different feed sizes of the Rosin-Rammler distribution moduli of 0.5, 0.7 and 1.0 with a top size of 38.1 mm shown in Fig. 10 were used for the simulation test. The weight percentages for less than 200-mesh of feed coal are 13.2%, 5.0% and 1.2%, respectively. The simulated results for a large-scale mill \((D = 1780 \text{ mm})\) are shown in Fig. 11 where computation was performed at a fixed vane angle. The finer feed coal (i.e. the lesser value of \(n\)) is the finer product. Furthermore, within a range of 80 ~ 100% mill capacity, decreasing mill capacity results in a finer product. However, the fineness is almost independent of mill capacity below an 80% mill load.

On the other hand, the relative circulating load expressed by \(F^*/G^*\) where the coal flow rate at the grinding zone was divided by the make up feed rate \(G\) at 100% mill capacity, and a finer feed size results in lower coal flow rates in the grinding zone. In particular, within the range of 80 ~ 100% mill capacity, the coal flow rate in the grinding zone varies with the mill capacity. These results are different from those obtained by grinding in dry and wet tube ball mills. The performance of a tube ball mill is not strongly affected by the feed size distribution because it is a fine grinding mill. In general, a roller mill is considered to be a relatively coarse grinding mill with internal classifiers in which coarser particles are recycled to the grinding zone and finer particles are recovered as the product, minimizing over-grinding. Hence, it appears that the mill performance depends on the coal particle feed size. Moreover, this is one of the reasons why a roller mill requires less mill power than a tube ball mill. A tube mill circuit is usually not operated at such
Fig. 12 Effect of the total crushing load on fineness for a large-scale mill (simulation)

a circulating load \((1 + C)\) as \(5 \sim 10\) in roller mills\(^9\).

4. 3 Effect of crushing loads

Figure 12 shows the effect of the total crushing load \(M\) on the pulverized-coal fineness. The effect of \(M\) on the pulverized-coal fineness and coal flow rate at the grinding zone is marked over the range of 80\% relative mill capacity. Especially at 100\% relative mill capacity, a 22\% reduction in \(M\) results in a substantially coarser product, and the coal flow rate in the grinding zone increases by approximately 1.6 times.

Furthermore, a crushing load 10\% higher than the design value results in greater pulverized-coal fineness and approximately a 10\% reduction in \(F'/G^*\). On the other hand, at low relative mill capacity, less than 70\%, pulverized-coal fineness, and \(F'/G^*\) are almost independent of \(M\) over the range of \(M/M^* = 0.78\) to \(M/M^* = 1.1\).

5. Conclusion

The mathematical model previously developed for a ring ball mill was further refined by introducing the scale-up laws on grinding and classification actions. The present steady-state simulation model can describe the operating behavior within the mill for a given mill.

Nomenclature

\[
\begin{align*}
A & : \text{air flow rate} \quad [\text{kg/min}] \\
A^* & : \text{base air flow rate} \quad [\text{kg/min}] \\
A_i & : \text{absolute rate of breakage of size } i \quad [\text{g/min}] \\
a & : S_i \text{ parameter} \\
B_i & : \text{cumulative breakage distribution parameter} \\
b_{ij} & : \text{fraction of material just broken from the size interval } j \text{ which appears in size interval } i \text{ (smaller size)} \\
b_i & : \text{constant} \\
C & : \text{circulation ratio at secondary classification zone} \\
C' & : \text{circulation ratio at primary classification zone} \\
C_i & : \text{net circulation ratio} \\
c_i & : \text{partial separation efficiency of size } i \text{ at secondary classification} \\
c_i' & : \text{partial separation efficiency of size } i \text{ at primary classification} \\
D & : \text{mean diameter} \quad [\text{mm}] \\
D_c & : \text{diameter of the cyclone-type classifier} \quad [-] \\
d & : \text{diameter of the grinding ball} \quad [\text{mm}] \\
F & : \text{coal flow rate at the classifier inlet} \quad [\text{kg/min}] \\
F' & : \text{coal flow rate at the grinding zone} \quad [\text{kg/min}] \\
f_i & : \text{wt. fraction of size } i \text{ in the combined feed of raw coal and secondary classifier tailings} \quad [-] \\
f_i' & : \text{wt. fraction of size } i \text{ in feed to the grinding zone} \quad [-] \\
G & : \text{coal feed rate} \quad [\text{kg/min}] \\
G^* & : \text{base coal feed rate} \quad [\text{kg/min}] \\
g & : \text{acceleration due to gravity} \quad [\text{m}^2/\text{s}] \\
g_i & : \text{wt. fraction of size } i \text{ in make-up feed} \quad [-] \\
H & : \text{vane height} \quad [\text{m}] \\
H.G.I & : \text{Hardgrove grindability index} \quad [-] \\
k & : \text{scale-up factor} \quad [-] \\
k_m & : \text{largest value of the scale-up factor} \quad [-] \\
k_0 & : \text{empirical factor} \quad [-] \\
k_1, k_2 & : \text{constants} \quad [-] \\
L & : \text{outlet skirt length} \quad [\text{m}] \\
M & : \text{crushing load} \quad [\text{N}] \\
M^* & : \text{base crushing load} \quad [\text{N}] \\
N & : \text{distribution constant} \quad [-] \\
p_i & : \text{wt. fraction of size } i \text{ in feed to the secondary classifier} \quad [-] \\
Q & : \text{through-put} \quad [\text{kg/min}] \\
Q_{H} & : \text{through-put of Hardgrove mill} \quad [\text{kg/min}] \\
Q_n & : \text{through-put of } k/k_m = 0.5 \quad [\text{kg/min}] \\
Q_{sim} & : \text{simulated through-put} \quad [\text{kg/min}] \\
q & : \text{wt. fraction} \sim 200\text{-mesh in mill output} \quad [-] \\
q^* & : \text{base wt. fraction} \sim 200\text{-mesh in mill output} \quad [-] \\
q_i & : \text{wt. fraction of size } i \text{ in mill output} \quad [-] \\
S_{16\times20} & : \text{the specific rate of breakage of } 16\times20\text{-mesh material} \quad [\text{\$/min}] \\
S_i & : \text{specific rate of breakage of size } i \quad [\text{\$/min}] \\
S_{16\times20} & : \text{the specific rate of breakage of } 16\times20\text{-mesh material} \quad [\text{\$/min}] \\
T & : \text{coal flow rate from secondary classification zone to the mill} \quad [\text{kg/min}] \\
\]
\[
\begin{align*}
T' & : \text{coal flow rate from primary classification zone to the mill} \quad \text{[kg/min]} \\
\tau_i & : \text{wt. fraction of size } i \text{ in secondary classifier tailings} \\
\tau_i' & : \text{wt. fraction of size } i \text{ in primary classifier tailings} \\
u_0 & : \text{air velocity at the classifier inlet} \quad \text{[m/s]} \\
W & : \text{hold-up in the mill} \quad \text{[kg]} \\
W_i & : \text{wt. fraction of size } i \text{ in hold-up} \\
x & : \text{particle size} \quad \text{[\mu m]} \\
x_i & : \text{particle size of interval } i \quad \text{[\mu m]} \\
x_{50} & : \text{critical cut size} \quad \text{[\mu m]} \\
x_{50}^* & : \text{base cut size of primary classification} \quad \text{[\mu m]} \\
x_{50}^{**} & : \text{base cut size of secondary classification} \quad \text{[\mu m]} \\
\alpha & : S_i \text{ parameter} \quad [-] \\
\beta & : B_{ij} \text{ parameter} \quad [-] \\
\gamma & : B_{ij} \text{ parameter} \quad [-] \\
\phi & : B_{ij} \text{ parameter} \quad [-] \\
\theta & : \text{vane angle} \quad \text{[degree]} \\
\omega & : \text{rotational speed of mill} \quad \text{[rpm]}
\end{align*}
\]

References

7) ASTM Designation: D491~71 (1980).