A study on grinding and energy input in stirred media mills

Jie Zheng, Colin C. Harris, P. Somasundaran
Henry Krumb School of Mines, Columbia University, New York, NY 10027, USA
Received 18 December 1994; accepted 9 June 1995

Abstract

Grinding and energy input in stirred media mills are studied as functions of grinding time, stirring speed, media size and density, solid concentration, impeller and tank dimensions and design, and other relevant variables. Ground product size and surface area are determined with respect to the above variables. Changes in energy input and media/pulp rheological properties during grinding are described. The best conditions for grinding limestone in the laboratory stirred media mills have been identified. Equations for correlations involving power and modified Reynolds numbers have been established.

Keywords: Grinding; Energy input; Stirred media mills; Ground product size; Rheological properties

1. Introduction

Stirred media mills are used in numerous industries because of their high energy efficiency, fine and ultrafine grinding ability, and reduced contamination. In view of their growing importance, basic research on power characteristics of stirred media mills has been carried out [1,2]. In this research, the torque required to rotate impellers immersed in dense particulate media with supernatant versus impeller rotational speed has been found to display four regions marked by sharp transitions: transition from static to dynamic friction; channelling; dispersing; and centrifuging. Equations, including dimensionless group correlations of power and modified Reynolds number, have been established for correlating power, speed, impeller and tank dimensions and design, media size and density, solid concentration, and other relevant variables. Scale-up guidelines for stirred media mills with respect to power consumption are proposed on the basis of the correlations and an example of power consumption scale-up has been provided. From the results obtained, it is clear that the relationships between grinding and energy input as functions of the operating variables require systematic study.

2. Experimental

The stirred media mill employed is illustrated in Fig. 1. A wide range of impeller designs can be accommodated by interchangeable fittings on the drive shaft, and two typical impeller designs used are shown in Fig. 2. A water bath is used for temperature control. Torque is measured by torque pick-up and indicator, and speed control is obtained by means of a d.c. motor with a rectifier and voltage regulator. Power \( P \) is calculated from the measured net torque \( \tau \) (gross torqu...
where \( d_{MA} \) is the mean diameter of the area distribution, which is calculated according to

\[
d_{MA} = \frac{\sum V_i}{\sum (V_i/x_i)} \tag{3}
\]

where \( V_i \) is volume percent in \( i \) size interval and \( x_i \) is the mean diameter of interval \([3]\).

The specific surface area was also determined by Quantasorb (based on the multiple point BET method) and the Fisher sub-sieve sizer (on the basis of the principles of air flow through porous media) for comparison.

To present the grinding results, three parameters defined below, increase of specific surface area \((\Delta S)\), volume-based energy or specific energy \((E_u)\) and energy efficiency \((E_f)\), are used

\[
\Delta S = S_p - S_f \tag{4}
\]

where \( S_p \) and \( S_f \) are the specific surface area of the product and feed, respectively.

\[
E_u = \frac{E}{V} \tag{5}
\]

where \( E \) is the energy input during grinding and \( V \) is the volume of ground material.

\[
E_f = \frac{\Delta S}{E_u} \tag{6}
\]

### 3. Results and discussion

#### 3.1. Effect of grinding time

The effect of grinding time on the product size distribution was studied by conducting a series of grinding tests at different grinding times with other conditions maintained constant. Size distributions obtained for grinding times of 5, 10 and 15 min are shown in Fig. 3 along with that for the feed. As grinding time is extended, the product size distribution curve, as expected, shifts to finer sizes, resulting in an increase of the specific surface area. Table 1 shows the values of specific surface area determined by different methods for ground product under 106 \( \mu \)m.

<table>
<thead>
<tr>
<th>Grinding time (min)</th>
<th>Specific surface area ((m^2/cm^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BET method</td>
</tr>
<tr>
<td>5</td>
<td>2.31</td>
</tr>
<tr>
<td>15</td>
<td>5.80</td>
</tr>
</tbody>
</table>
3.2. Effect of impeller rotational speed

The effect of impeller rotational speed on grinding limestone without initial supernatant liquid is shown in Fig. 4. As impeller speed is increased both product surface area and energy input increase, but energy efficiency declines. This finding, that higher speed results in lower energy efficiency, is in accordance with the results reported by Mankosa et al. [4] and Gao and Forsberg [5]. However, if the objective is to obtain higher specific surface area in a given grinding time, then higher speed is needed.

The combined effects of grinding time and stirring speed are shown in Fig. 5. Both lower speed and shorter grinding times give better energy efficiency. Energy efficiency as a function of the number of revolutions (Nt) is shown in Fig. 6 and a rough correlation is that energy efficiency is proportional to the number of revolutions to \(-0.57\) power.

Fig. 7 shows the results of grinding limestone with initial supernatant liquid in stirred mills. The average torque versus speed curve displays several distinct regions, in agreement with the results reported by Zheng et al. [1] for a loading of glass beads only with supernatant liquid. In that case, it was observed that the process passes through four regions: transition from static to dynamic friction; channelling; dispersion; and centrifugation. The drop in torque from channelling to dispersion region can be explained by media dispersion into the supernatant causing a drop in concentration and thus a decrease in viscosity.

Stirring speeds chosen for grinding test with supernatant condition were 260, 500 and 1000 rpm, which correspond respectively to: channelling; onset of suspension; and full
However, grinding energy or specific energy was found to be almost the same for the case of 260 and 500 rpm, which can be explained by the drop in torque due to the transition from channeling to dispersing region, while higher energy consumption was obtained at a speed of 1000 rpm. Therefore, the best energy efficiency is obtained for grinding at the stirring speed of 500 rpm, which corresponds to the lowest point in torque versus speed curve which occurs in the 'onset of suspension' region.

3.3. Effect of solid concentration

From the discussion of the cases with and without supernatant liquid, it is evident that total solid (combination of media and particles) concentration is a very important factor in a wet grinding operation because of its direct influence on the ground product fineness and operating power or energy consumption. The effect of solid concentration on torque during the grinding process is shown in Fig. 8. The torque increases with increasing solid concentration over the entire grinding period studied. It is noted that the changes in solid concentration are produced only by means of water dilution, while the media and particle weight or volume remains the same.

Effect of the solid concentrations by volume (60% to 80%) on the grinding limestone is shown in Fig. 9. It is seen that the product surface area increases with solid concentration from 60 to 75% and then decreases a little at 80%. Observation through the transparent tank during the stirring test at the solid concentration of 80% reveals that only the solids (media and particles) around the center of the impeller are stirred while beyond the impeller pins the solids remain almost stationary. It is those nearly unground particles in that stationary region that account for the decrease in product fineness.

Volume-based energy increases with increasing solid concentration as shown in Fig. 9, which also summarizes the results shown in Fig. 8. From Fig. 9, it can be concluded that the best energy efficiency is at the concentration of 65%, which corresponds to the conditions when there is minimal initial supernatant liquid in the system.

Dry grinding (i.e. concentration 100%) results are also shown in Fig. 9. In comparison with wet grinding, dry grinding results in lower product fineness, higher energy consumption and the lowest energy efficiency.

3.4. Effect of ratio of media to particle volume

Total solid (media and particles) concentration at constant ratio of media to particle volume has been found to be important. The following series of experiments were designed to study the effect of ratio of media to particle volume on specific surface area, specific energy and energy efficiency. Here, the solid concentration is fixed while the ratio of media to particle volume is changed from test to test, and the volume of particles decreases while that of media increases with increasing dispersion region. Product surface area shown in Fig. 7 was found to increase when the stirring speed was raised while maintaining other conditions constant. This result is similar to that found in the case without supernatant liquid in Fig. 4.
The effect of media density on the grinding of limestone is shown in Table 2. It is seen that higher media density results in slightly higher specific surface area but also in much higher (almost double) energy consumption, and thus much lower energy efficiency in comparison with less dense media. During the experimentation, it was observed that steel media produced much greater heat and noise than the glass media accounting for greater wasted energy.

\[ R = \frac{1 - \epsilon_m}{\epsilon_m(1 - \epsilon_p)} \]  

where media packing porosity is \( \epsilon_m \) and particle (limestone) packing porosity is \( \epsilon_p \). In this case, \( \epsilon_m = 0.4 \) and \( \epsilon_p = 0.47 \) give \( R = 2.8 \). Consequently, the best grinding conditions occur when the voids in the grinding media packing are just filled with the particles.

3.5. Effect of media size

Fig. 11 shows the effect of the media size on grinding and energy consumption. The product surface area becomes greater as the media size is decreased. This tendency continues until the media size becomes too small to cause particle fracture effectively. The use of finer media also results in reduced energy input probably due to increased ‘fluidity’. These results agree with those reported by Orumwense and Forssberg [6] for dolomite samples ground in an annular ball mill.

Fig. 11 also shows that the best energy efficiency is obtained at media size 2 mm. Feed mean size calculated from the volume distribution is 166 \( \mu \)m, so that best ratio of media to feed size is 12:1, which is nearer to the middle of the optimum range of 7:1 than to the maximum 20:1 suggested by Conley [7]. However, our best ratio is less than the value of 20:1 recommended by Mankosa et al. [8], possibly due to different minerals and media density, in their case coal and steel balls.

3.6. Effect of media density

The effect of media density on the grinding of limestone is shown in Table 2. It is seen that higher media density results in slightly higher specific surface area but also in much higher (almost double) energy consumption, and thus much lower energy efficiency in comparison with less dense media. During the experimentation, it was observed that steel media produced much greater heat and noise than the glass media accounting for greater wasted energy.

3.7. Effect of impeller and tank dimensions

Fig. 12 shows the effect of impeller and tank dimensions on the torque. It is clear that torque or power input depends principally on the impeller diameter but hardly on the tank diameter. However, the product fineness as shown in Fig. 13 relies chiefly on the ratio of tank to impeller diameter. The product fineness decreases with increasing the ratio. This finding is also demonstrated by the data for \( \Delta S \) given in Table 3. Therefore, the closer the impeller to the tank wall or the lower the ratio of tank to impeller diameter, the more complete is grinding in the mills. Table 3 also shows specific energy and energy efficiency. Specific energy declines with increase in the ratio of impeller to tank diameter. As a result, maximum energy efficiency is obtained at the highest ratio. However, comparing energy efficiency with \( \Delta S \) value for the case of 11.8 cm tank for 10 cm impeller, it can be seen that the specific surface area increases by a factor of 2.5 but energy...
3.8. Effect of impeller design

The effect of impeller design is shown in Table 4. It is seen that use of the full 4-pin impeller results in higher both $\Delta S$ and $E_U$ value. Consequently, energy efficiency is almost the same for both cases.

3.9. Effect of pulp viscosity

The procedure to determine the effective viscosity during the grinding process rather than at its termination has been described by Zheng et al. [1,2]. This procedure uses the non-Newtonian power law equation involving consistency and flow index, which are estimated on the assumptions that shear rate is proportional to impeller speed and shear stress proportional to torque. The effective viscosity can be related to the consistency and flow index by the equation

$$\mu = K a^{-1} N^{n-1}$$

Power consumption with respect to stirred media mills can be described by the following equation [1]

$$P = C K a^{-1} N^{n+1} D^3$$

Combining Eqs. (8) and (9), the effective viscosity can be represented by

$$\mu = \frac{P}{CN^2D^3}$$

This equation can be obtained more directly from the power and modified Reynolds number correlation, but that route does not enable the estimation of the consistency and flow index values. The effective viscosity values have been calculated according to Eq. (10), and the relationship between effective viscosity and solid concentration is shown in Fig. 14. The effective viscosity increases with increasing solid concentration. Circular symbols represent the experimental data while the continuous line shows the calculated relationship according to Eq. (11) correlated from the experimental data

$$\mu = 13252 \mu e^{0.725}$$

It is noted that this equation for media/pulp system is different from that for media only [1].

3.10. Correlation between grinding and energy input

Energy efficiency and increase of specific surface area are respectively plotted as a function of volume-based energy in Figs. 15 and 16. The straight lines in the figures are drawn by using Eqs. (12) and (13)

$$E_f = 10.56 (E_U)^{-0.4}$$

$$\Delta S = 9.27 (E_U)^{0.54}$$

The regression coefficient for Eq. (12) is 0.92 and that for Eq. (13) 0.95, and both standard deviations are 13%.
Grinding and energy input in stirred media mills have been studied as functions of grinding time, stirring speed, media size and density, solid concentration, ratio of media to particle volume, impeller and tank dimensions and design, and other relevant variables.

Lower stirring speed gives better energy efficiency for grinding without supernatant liquid. However, for the case of grinding with supernatant, the best energy efficiency occurs at the stirring speed corresponding to the lowest point in torque versus speed curve, in the 'onset of suspension' region.

The solid concentration for the best energy efficiency corresponds to the value at which there is minimal supernatant liquid in the system. Wet grinding is more energy efficient than dry grinding.

The critical ratio of media to particle volume for the best energy efficiency is 2.8 for grinding limestone using glass beads as media and the equation giving this critical ratio of filling is confirmed.

The optimum ratio of media to particle size is 12:1 for the case of grinding limestone using glass beads.

In the same size range, glass media is more energy efficient for grinding limestone than steel.

The torque or power input depends principally on the impeller diameter but hardly on the tank diameter. The closer the impeller to the tank wall or the lower the ratio of tank to impeller diameter, the finer the product. However, the maximum energy efficiency may be obtained at the highest ratio of tank to impeller diameter due to the lowest power input.

Both greater product fineness and higher energy consumption are obtained by using the full 4-pin impeller rather than half 4-pin impeller, but the energy efficiency is not much affected by such difference in this impeller design.

The relationship between effective viscosity and total solid concentration has been determined. Effective viscosity is proportional to the solid concentration to the 3.7 power.

The regression power constants reported by Stehr and Schwedes [9] for a horizontally oriented stirred ball mill, were -0.228 and 0.772, respectively, while the constants found for the mill used in this investigation are shifted downwards by about 0.2. The spread of the correlated points results from a wide range of operating conditions the detailed effects of which are still to be evaluated. However, the points in both figures which result from lower solid concentration, smaller media size, higher density and dry grinding, are not included in the correlations probably due to their different grinding mechanism. The results from using half 4-pin impeller is included in the correlations, which implies that grinding may not be too dependent on the design of this type of impeller.

### 3.1. Dimensionless correlation

Specific energy (volume or weight based energy) input has been considered as the basic criterion for reliable scale-up of stirred media mills [10-12]. This specific energy can be obtained by introducing average power. Dimensionless group correlations of power and modified Reynolds number have been established for correlating the parameters influencing the power consumption for media and liquid system in stirred mills [1]. Similarly, power and Reynolds numbers for media, particles and liquid system can be calculated according to the following equations, respectively

$$ N_p = \frac{P}{\rho N^3 D^5} $$

$$ Re = \frac{ND^2 \rho}{\mu} $$

where $\mu$ is effective viscosity, computed using the procedure developed in an earlier paper [1] and $\rho$ is the total density of the media and pulp system. Power and Reynolds numbers for grinding limestone are correlated by a single straight line of slope -1 for all studied variables in the case of full 4-pin impeller.

### 4. Conclusions

The torque or power input depends principally on the impeller diameter but hardly on the tank diameter. The closer the impeller to the tank wall or the lower the ratio of tank to impeller diameter, the finer the product. However, the maximum energy efficiency may be obtained at the highest ratio of tank to impeller diameter due to the lowest power input.

Both greater product fineness and higher energy consumption are obtained by using the full 4-pin impeller rather than half 4-pin impeller, but the energy efficiency is not much affected by such difference in this impeller design.

The relationship between effective viscosity and total solid concentration has been determined. Effective viscosity is proportional to the solid concentration to the 3.7 power.
The correlation between grinding and energy input can be described by the equations derived for energy efficiency and increase of specific surface area respectively as a function of volume-based energy for most cases studied. Power consumption for grinding in stirred media mills can be described by correlations involving power and modified Reynolds numbers that relate the relevant variables studied.

5. List of symbols

- volumetric concentration of solids (media and particle combined)
- impeller geometry constant
- media particle diameter
- mean diameter of area distribution
- impeller diameter
- energy input
- energy efficiency
- volume-based energy (specific energy)
- consistency coefficient
- power law index
- impeller rotational speed
- power number
- Reynolds number
- power
- ratio of media to particle volume
- specific surface area
- specific surface area of feed
- specific surface area of product
- increase of specific surface area
- grinding time
- tank diameter
- volume of ground material
- volume percent in a size interval
- mean diameter of interval

Greek letters

- impeller shear rate constant
- media packing porosity

Acknowledgements

This research has been supported by the Department of Interior's Mineral Institute Program administered by the United States Bureau of Mines through the Generic Mineral Technology Center for Comminution under Grant Number G1145249.

References