Analysis of Raw Material Flow with Axial Direction in Continuous Drum Mixer for Sintering Process

Masaki HARA, Takazo KAWAGUCHI, Masaru MATSUMURA and Chikashi KAMIJO

2) Head office, Sumitomo Metal Industries, Ltd., 1-8-11 Harumi, Chuo-ku, Tokyo 104-6111 Japan.

(Received on October 2, 2008; accepted on February 4, 2009)

The granulation process is known to be important to achieve high productivity in sinter process because the granulation of sinter mixture is connected with permeability of sinter bed. Past studies on the granulation in the drum mixer for sintering process mostly used the batch type drum mixer, hence their studies were on the raw material behavior for cross-section of the drum mixer. In contrast there were few reported on the raw material behavior for a drum axial and a residence time in a continuous type drum mixer. The raw material flows and the residence times have been investigated experimentally by using a continuous type drum mixer, and results were compared to those by the theory predicts suggested by Saeman. In addition, the effects of the ring dam fitted to the discharge end on the residence time and granulation improvement were investigated. As a result, with the drum set at the low angle, the observed residence times were shorter than the theory predicts. This is due to the level of the raw material tapering off as it reaches the discharge end. Thus, by newly considering angle ψ between the raw material surface and the drum mixer, the residence time was accurately estimated. Also, with the drum set the low angle, the ring dam fitted to the discharge end prevented any tapering, resulting in the longer residence time and greatly improved granulation.

KEY WORDS: granulation; sinter; drum mixer; iron ore; residence time; ring dam.

1. Introduction

Recently, iron ore imported from Australia comprises a large percentage of Pisolite ore and Marra Mamba ore which are types of limonite ore, as the reserves of low phosphorus Brockman type ores are depleted. The increase of the limonite ore in sintering bed causes the lowering of permeability and yield. As a result, the sinter ore productivity is decreased. On the other hand, sinter ore is needed to increase production in order to increase the blast furnace production due to demand in steel worldwide. The granulation process is important to achieve high productivity in sinter process because the granulation of sinter mixture is connected with permeability of sinter bed. Past studies on granulation in the drum mixer for sintering process mostly used the batch type drum mixer, hence their studies were on the raw material behavior for cross-section of the drum mixer. In contrast there were few reports on the raw material behavior for a drum axial and a residence time in a continuous type drum mixer. The raw material flows and the residence times have been investigated experimentally by using a continuous type drum mixer, and results were compared to those by the theory predicts suggested by Saeman. In addition, the effects of the ring dam fitted to the discharge end on the residence time and granulation improvement were investigated. As a result, with the drum set at the low angle, the observed residence times were shorter than the theory predicts. This is due to the level of the raw material tapering off as it reaches the discharge end. Thus, by newly considering angle ψ between the raw material surface and the drum mixer, the residence time was accurately estimated. Also, with the drum set the low angle, the ring dam fitted to the discharge end prevented any tapering, resulting in the longer residence time and greatly improved granulation.

2. Experimental Method

2.1. Equipment and Raw Material

The schematic of the drum mixer for sintering process is shown in Fig. 1. This device could change the rotation speed, the drum angle, the feed rate of the raw material, and the ring dam height, respectively. Also, the weight of the residence raw material could be continuously measured by a load cell below the device. Furthermore, an internal wall surface of the drum mixer was self-coating of the raw material like a commercial plant, and all experiments were studied at steady-state flow condition attained prior to measure.

A general sinter mixture was used in the experiments. Size distributions and median diameter of the raw material before and after adding water were shown in Table 1, where the water was added to obtain 7.5% moisture by using a high-speed agitating mixer.
2.2. Measurement Method of Tracer Stimulus–Response Test

Operating conditions of the drum mixer are shown in Table 2. Influence of the feed rate and the ring dam fitted to the discharge end on the residence time was observed. In the steady-state raw material flow condition, 1.0 kg of tracer was injected into the feed end at arbitrary zero time and discharged materials were simultaneously sampled. Here, the tracer used was reagent zinc oxide (ZnO), and it was made to adhere to the raw material by adding the water in the drum mixer. The injection time was assumed to be short enough for approximately ideal impulse input. The experiment time was 5 min and samples were taken at 10 s intervals. Then the ZnO concentration of them was measured.

2.3. Measurement Method of Mean Residence Time and Mean Occupation in Drum Mixer

Operating conditions of the drum mixer are shown in Table 3. Operating conditions of drum mixer when mean residence time measure.

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Feed rate [kg/min]</th>
<th>Rotation speed [rpm]</th>
<th>Drum angle [°]</th>
<th>Ring dam height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50-200</td>
<td>10-25</td>
<td>0.9-5.4</td>
<td>0-120</td>
</tr>
</tbody>
</table>

2.4. Measurement Method of Occupation Area Ratio with Axial Direction in Drum Mixer

In the steady-state raw material flow condition, the feeding raw materials and the rotating drum mixer were simultaneously stopped, and depths of the raw material layer within the drum mixer, at 0.1, 0.5, 1.0, 1.5, 2.0, 2.5 and 2.9 m spot from discharge end were measured (Fig. 2). The depth in 3.0 m spot was as measured in the 2.9 m spot and the depth in 0 m spot was similar to zero when there was no ring dam. Occupation area ratio with axial direction in drum mixer is given by Eqs. (3) and (4).

\[ \theta_{\text{obs}} [\text{vol\%}] = \frac{W}{\rho \cdot L \cdot \rho \cdot D^2 / 4} \times 100 \quad \text{(2)} \]

\[ \varphi [\text{radian}] = 2 \times \text{acos} \left( 1 - \frac{2h}{D} \right) \quad \text{(3)} \]
\[ h: \text{ Depth of the raw material layer in cross-section of \ drum mixer [mm]} \]

\[ \varphi: \text{ Central angle in cross-section of the \ drum mixer [radian]} \]

\[ \theta_{z}: \text{ Occupation area ratio in cross-section of the \ drum mixer [area\%]} \]

2.5. Measurement Method of Granulation Index

The quasi-particle discharged from the drum mixer was collected in the steady-state raw material flow condition. The particle size distributions measurement of the raw material and the quasi-particle were measured, after dried for over 4 h at 383 K, by sieving for 15 s using screen mesh of 9.5, 6.7, 4.0, 2.0, 1.0, 0.5 and 0.25 mm without the tap.

Granulation index (\(GI_{0.25}\)), defined as Eq. (5), was used for the estimation of the granulation. What is meant is that the granulation improves with the increase of \(GI_{0.25}\).

\[
GI_{0.25} \text{[mass\%]} = \left( 1 - \frac{B_{0.25}}{A_{0.25}} \right) \times 100 \quad \text{(5)}
\]

\(A_{0.25}\): -0.25 mm ratio of raw material before granulation \([\%]\)

\(B_{0.25}\): -0.25 mm ratio of raw material after granulation \([\%]\)

3. Results

3.1. Occupation Area Ratio with Axial Direction in Drum Mixer

Figures 3 and 4 show the depth of the raw material layer with axial direction in the drum mixer and the occupation area ratio with axial direction in the drum mixer, respectively, when the drum angle is changed to 5.4° from 0.9° with the rotation speed and feed rate set at 20 rpm and 100 kg/min. With the drum set at a high angle (over 3.6°), the depth of the raw material layer with axial direction in the drum mixer were almost constant except for the discharge end proximity (0.1 m spot from the discharge end: Site of about 0.2 times of drum diameter) (Fig. 3). On the other hand, with the drum set at a low angle (under 1.8°), those were tapered off as they reached the discharge end (Fig. 3). As a result, with the drum set at a low angle, the occupation area ratio with axial direction in the drum mixer was tapered off till the 2.5 m spot from the discharge end, site of about 4.2 times of the drum diameter (Fig. 4).

3.2. Residence Time Distribution in Drum Mixer

Figure 5 shows the influence of feed rate on the residence time distribution with the drum angle fixed at 1.8°. Also, it seems to collect the tracer of about 80% charge rate from the discharged raw material (Fig. 6). Consequently, this tracer stimulus-response test is considered reasonable, because it seemed to collect most of the input tracer. The raw material flows in the drum mixer were similar the piston flow, because one sharp peak was detected. Also, the residence time distributions were almost constant when the drum mixer rotation speed and the drum angle were fixed, even if the feed rate changed (Fig. 5).

Figure 7 shows the influence of the ring dam at discharge end on the residence time distribution with the drum angle fixed at 1.8°. Though one peak was detected, even if the ring dam was fitted, and the detection time of the peak was shifted in the long term. Also, the peak tended to be...
extended when the height of the ring dam was increased. However, the residence time distributions were almost the same, when each residence time was made the dimensionless by dividing each of the mean residence time (Fig. 8). Thus, the raw material flows in the drum mixer were similar the piston flow, even if the ring dam was fitted at the discharge end.

3.3. Influence of Factors on Residence Time in Drum Mixer

3.3.1. Influence of Feed Rate of Raw Material on Residence Time

The relationship between the feed rate of the raw material, $Q$, and the weight of the residence raw material in the drum mixer, $W$, is shown in Fig. 9. Weight of the residence raw material was proportional to the feed rate when the drum mixer rotation speed and drum angle were fixed.

The relationship between the feed rate of raw material, $Q$, and the mean residence time, $t_{obs}$, is shown in Fig. 10. The residence times were almost constant when the drum mixer rotation speed and the drum angle were fixed, even if the feed rate was changed. Thus, the mean residence time is not dependent on the feed rate of raw material.

3.3.2. Influence of Rotation Speed of Drum Mixer and Drum Angle on Residence Time

The influence of the rotation speed on the mean residence time is shown in Fig. 11. The mean residence time was increased when the rotation speed became slower. The influence of the drum angle on the mean residence time is shown in Fig. 12. The mean residence time was increased when the drum angle became lower.

3.3.3. Influence of Ring Dam at Discharge End on Residence Time

The influence of the ring dam at discharge end on the mean residence time is shown in Fig. 13. The mean residence time was increased when the ring dam was heightened by increasing the residence raw material in the drum mixer. Also, the mean residence time was decreased, as the
Feed rate of the raw material was increased when the ring dam height was a constant. Figure 14 shows the shift of occupation area ratio with axial direction in the drum mixer as the ring dam was heightened. The raw material layer depths at 0 m spot and 3.0 m spot from the discharge end were interpolated because they could not be directly measured since the drum mixer stopped. The depth of raw material layer with axial direction at 0 m spot was interpolated in a gradient of that of 0.5 m spot and 1.0 m spot from discharge end, and the depth at 3.0 m spot was interpolated in the same depth at 2.5 m spot. When the feed rate was 100 kg/min, the occupation area ratio with axial direction in the drum mixer increased as the ring dam was heightened. Especially, the occupation area ratio with axial direction in the drum mixer was almost constant from the discharge end to the feed end when the ring dam height was 60 mm, and this was drastically increased from 0 m spot to 1.5 m spot from the discharge end when the ring dam height was 120 mm. Also, when the feed rate was 200 kg/min, the occupation area ratio with axial direction in the drum mixer increased as the ring dam was heightened, and it was almost double the occupation area ratio with axial direction in the drum mixer at 100 kg/min in the feed end site. However, the occupation area ratio with axial direction in the drum mixer was still tapered off as they reached the discharge end, even if the height was 120 mm.

3.4. Effect of Ring Dam at Discharge End on Granulation

The granulation index ($G_{I_{0.25}}$) change in the mean residence time extension by the ring dam at discharge end is shown in Fig. 15. The mean residence time was increased to 1.8–2.8 min from 1.3 min by the ring dam fitted to the discharge end. As a result, $G_{I_{0.25}}$ was increased to 17–25%, that is to say, granulation was improved by the ring dam.

4. Discussion

4.1. Raw Material Flow with Axial Direction in Drum Mixer

In this chapter, the raw material flow with axial direction in the drum mixer is considered. As it was explained in Chap. 3.2, the raw material flow with axial direction in the drum mixer seems to be similar to the piston-flow. The piston-flow which describes here means that the raw material flows without feed back. Therefore, though the raw material with the drum cross section direction was thoroughly mixed, the raw material with axial direction might be hardly mixed at all.

Now, the relationship between the feed rate of raw material, $Q$, with the occupation area ratio in cross-section of the drum mixer, $\theta_z$, and the axial transport velocity, $V_z$, was represented by Eq. (6).

$$Q [\text{kg/min}] = \rho \cdot V_z \cdot \theta_z$$

As it was shown in Fig. 14, the occupation area ratio, $\theta_z$, was not become the same at any points of the drum mixer and was changed from the feed end to the discharge end. Also, those changes were different between the feed rate of raw material was 100 kg/min with that was 200 kg/min. In order to analyze this difference, the occupation rate at a certain point in the drum mixer was defined as Eq. (7). The occupation rate profile is shown in Fig. 16. The occupation rate was almost 2.0 from feed end site to the middle ($i=3.0–1.5$ m). The occupation rate decreased from the middle to the discharge end site ($i=1.5–0$ m). Then, it became 1.0 at discharge end ($i=0$ m). Thus, when the feed rate is changed to 200 kg/min from 100 kg/min, the occupa-
The mean \( V_z \) at \( Q = 200 \text{ kg/min} \) doubles the mean \( V_z \) at \( Q = 100 \text{ kg/min} \). In other words, \( V_z \) at the feed end site to the middle \((i = 3.0–1.5 \text{ m})\) is constant velocity, even if the feed rate was changed. In contract, \( V_z \) at the discharge end \((i = 0 \text{ m})\) is proportional to the feed rate of the raw material, so \( V_z \) at the discharge end is constant, even if the feed rate was changed. However, \( V_z \) and \( \theta_z \) at the discharge end can be affected on the ring dam height. Thus, the ring dam can control \( V_z \) and \( \theta_z \) at the discharge end.

The summary of the above discussion is as follows. The raw material flow with axial direction in the drum mixer is similar to the constant velocity flow at the feed end site to the middle \((i = 3.0–1.5 \text{ m})\). From the middle to the discharge end, the occupation area ratio is changed by the ring dam height. The raw material overcomes the ring dam like the liquid flow overcomes.

### 4.2. Comparison between Estimated Formula and Observed Residence Time

On the basis of geometric analysis, Saeman\(^{19}\) suggested the theoretical formulas of the axial transport velocity, \( V_z \), and the residence time, \( t_{\text{cal}} \), of the pellet in the rotary kiln. These formulas are represented by Eq. (11) and Eq. (12).

\[
V_z [\text{m/min}] = \frac{\pi \cdot D \cdot n \cdot \alpha}{\sin \beta} \quad \text{.........(11)}
\]

\[
t_{\text{cal}} [\text{min}] = \frac{L}{V_z} = \frac{L \cdot \sin \beta}{\pi \cdot D \cdot n \cdot \alpha} \quad \text{.........(12)}
\]

\( n \): Rotation speed of drum mixer [rpm]
\( \alpha \): Angle of drum mixer [radian]
\( \beta \): Angle of repose of raw material [radian]

Joko \textit{et al.}\(^{16}\) reported that observed residence times were comparable to theoretical values suggested by Saeman. On the other hand, Suzuki \textit{et al.}\(^{15}\) reported that the axial transport velocity suggested by Saeman needs to be compensated by a correction factor (1.8 times) because of accelerating particles in the drum mixer. That is to say, the observed residence time was shorter than the theoretical values suggested by Saeman.

The comparison of the observed residence time, \( t_{\text{obs}} \), with the calculated residence time, \( t_{\text{cal}} \), is shown in Fig. 17. With the drum set at a high angle (over 3.6°), the observed residence times were almost the same as the calculated residence times. However, with the drum set at a low angle (under 1.8°), the observed residence times were up to 46% shorter than the theoretical values suggested by Saeman. These differences are due to the level of the raw material tapering off as it reaches the discharge end (droop effect at the discharge end) when the drum is set at a low angle. Saeman targeted the rotary kiln where there was enough length for the drum diameter \((L/D = 14, L = 7 \text{ feet and } D = 0.152 \text{ m})\). So, he thought that actual kilns usually operated with essentially uniform bed depth along their length, and nonuniformity from droop effect at the discharge end of the kiln was small and could be neglected, even if the drum angle set a low. Therefore, it seems that the theoretical formula could be approximated due to the occupation of the raw material being almost constant. Thus, Joko \textit{et al.}\(^{16}\) used enough length for the drum diameter \((L/D = 10)\), and those results were almost the same as the estimated residence time. Recently, however, the drum mixer for sintering process is set at a low angle \((< 2°)\) to increase the residence time. Also, it is not enough length for the drum diameter \((L/D = 3–5)\). Therefore, an angle between the raw material surface and the drum mixer, \( \varphi \), is important for the estimated residence time, and must be considered in the esti-
mated formula for the residence time.

Saeman suggested the estimated residence time, \( t \), which was considered the angle between the raw material surface and the drum mixer, \( \psi \), on the basis of geometric analysis by the taper type drum mixer. The estimated residence time, \( t \), is represented by Eq. (13)

\[
\psi = \frac{L}{V_z} = \frac{L \cdot \sin \beta}{\pi \cdot D \cdot n \cdot (\alpha + \psi \cos \beta)} \quad \ldots (13)
\]

In these experiments, \( \psi \) was calculated by the depth of the raw material layer at 0.5 m spot and 2.5 m spot from the discharge end. The relationships of the rotation speed and \( \psi \) and the drum angle and \( \psi \) were shown in Figs. 18 and 19, respectively. \( \psi \) was increased by lowering the rotation speed and the drum angle. \( \psi \) depended on the rotation speed and the drum angle, so the relationship between \( \psi \) and the \( n \cdot \alpha \) was plotted in Fig. 20. As a result, this relationship was correlated with Eq. (14).

\[
\psi [\text{radian}] = 0.0025 \cdot (n \cdot \alpha)^{-2} \quad \ldots (14)
\]

The result of comparing the observed residence time, \( t_{\text{obs}} \), with the estimated residence time, \( t \), calculated from Eqs. (13) and (14) is shown in Fig. 21. The observed residence time is consequently the same as the estimated residence time by using Eqs. (13) and (14). Therefore, it seems that the residence time in the drum mixer can be estimated by using Eqs. (13) and (14).

### 4.3. Occupation of Raw Material in Drum Mixer

It is important to know the influences of the drum diameter on the feed rate of raw material, \( Q \), and \( \psi \) when the residence time in the commercial drum mixer is designed. Then, the influences of the drum diameter on the feed rate and \( \psi \) was considered by comparing the occupation of the model drum mixer \( (D=0.6 \text{ m}) \) and the commercial drum mixer \( (D=4.5 \text{ m}) \).

Specifications and operating conditions of both drum mixers are shown in Table 4. Both drum mixers have the same drum angle, a similar Froude’s number and drum dimension \( (L/D) \). It was reported that the raw material behavior of cross-section in the drum is similar to the ratio between the gravity and the centrifugal force of the drum, namely the Froude’s number \( (\text{Eq. (15)}) \) is the same.\(^{14,21}\) For this concept to be accepted, when the drum diameter is made to be the \( D \) times, the new \( V_z \) becomes the drum diameter to the power of 0.5 multiplied by the original \( V_z \) from Eqs. (11) and (15). On the other hand, when the drum diameter is made to be the \( D \) times, the new occupation of cross-section in the drum becomes the drum diameter to the power of 2.0 multiplied by the original drum diameter. Therefore, when the occupation in the drum mixer is fixed by the increase in the drum diameter, the new feed rate must be equal to the ratio of the drum diameter to the power of 2.5 multiplied by the original feed rate. For example, the feed rate in the model drum mixer at \( D=0.6 \text{ m} \) must be 5.2 t/h for the feed rate 800 t/h in the commercial drum mixer.

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Model</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate [t/h]</td>
<td>6</td>
<td>800</td>
</tr>
<tr>
<td>Drum diameter [m]</td>
<td>0.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Drum length [m]</td>
<td>3.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Drum angle [°]</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Rotation speed [rpm]</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Froude’ number ( \times 10^2 ) [-]</td>
<td>3.8</td>
<td>4.6</td>
</tr>
<tr>
<td>( L/D ) [-]</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Bulk density [t/m(^3)]</td>
<td>1.60</td>
<td>1.85</td>
</tr>
</tbody>
</table>
mixer at \(D=4.5\) m.

\[
\text{Froude’s number [\(-\)]} = \frac{D \cdot n^2}{60^2 \cdot g} \tag{15}
\]

g : Apparent gravity [m/s\(^2\)]

The depth of raw material layer with axial direction in the commercial drum mixer and that in the model drum mixer, which was made dimensionless by the drum diameter, is shown in Fig. 22. In the model drum mixer and the commercial drum mixer, \(\psi\) formed from the feed end to the discharge end was similar. However, the depth of the raw material layer with axial direction in the model drum mixer was slightly deeper than the commercial drum mixer. It seems that this is due to the difference of the feed rate and the bulk density. Thus, the feed rate and the bulk density were compensated when the occupation was calculated from the raw material depth. Here, \(\psi\) and \(\psi\) are represented by following equations, respectively.

\[
\psi [\psi] = \frac{n}{n_c} = \frac{n \cdot \sqrt{D}}{42.3} \tag{16}
\]

\[
\Psi [\text{radian}] = 8.4 \times 10^{-7} \cdot (v \cdot \alpha)^{-2}
= 1.5 \times 10^{-3} \cdot (\sqrt{D \cdot n \cdot \alpha})^{-2} \tag{17}
\]

\(n_c\) : Critical rotation speed [rpm]

\(\psi\) measured in the commercial drum mixer is shown in Table 5. Here, \(\psi\) of the commercial drum mixer A and B were calculated by the depth of raw material layer at 3.5 m spot and 19.0 m spot, and the one at 2.5 m spot and 8.0 m spot from the discharge end, the discharge end, respectively. Also, Eq. (17) was described in Fig. 24, and \(\psi\) measured in the commercial drum mixer was plotted there. As a result, the observed results are shown as points on the graph that lie on the line produced from the calculation of \(\psi\) by using Eq. (17), and this estimated formula of \(\psi\) was accurately confirmed. Thus, the residence time can accurately be estimated by using Eqs. (13) and (17).

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate [t/h]</td>
<td>800</td>
<td>110</td>
</tr>
<tr>
<td>Drum diameter [m]</td>
<td>4.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Drum length [m]</td>
<td>25.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Drum angle [°]</td>
<td>1.8</td>
<td>1.15</td>
</tr>
<tr>
<td>Rotation speed [rpm]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Dimensionless rotation speed [-]</td>
<td>0.30</td>
<td>0.23</td>
</tr>
<tr>
<td>L/D [-]</td>
<td>5.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>

5. Conclusion

The raw material flows and the residence times have been investigated experimentally by using the continuous type
drum mixer for the sintering process, and were compared to the theoretical values suggested by Saeman. The followings are the summary of this work:

1. With the drum set at the low angle, the observed residence times were shorter than theoretical values suggested by Saeman. This is due to the level of the raw material tapering off as it reaches the discharge end. Thus, by newly considering angle \( \Psi \) between the raw material surface and the drum mixer, the residence time was accurately estimated by the following equations.

\[
t_{[\text{min}]} = \frac{L \cdot \sin \beta}{\pi \cdot D \cdot n \cdot (\alpha + \Psi \cos \beta)}
\]

\[
\Psi \ [\text{radian}] = 1.5 \times 10^{-3} \cdot (\sqrt{D \cdot n \cdot \alpha})^{-2}
\]

2. With the drum set at the low angle, the ring dam fitted to the discharge end prevented any tapering, resulting in longer residence time and greatly improved granulation.

REFERENCES