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Attrition rate of iron ore in the gas-solid fluidized beds with the wide size distribution

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Attrition characteristics of iron ore by air jet in gas-solid fluidized beds

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1. Introduction
2. Theory
3. Objective
4. Experiment
5. Result and discussion
6. Conclusion
1. Introduction

- Particle attrition in common process (Circulating Fluidized Bed Combustor)

- Recent and future thermal power plant:
  Circulating Fluidized Bed Combustor
  Integrated Gasification Combined Cycle

- Limestone: absorbent of CO₂ and sulfur
  (severe condition of CFB reactor)

- Attrition studies of the limestone progressed
  Jia *et al.* (2007); Montagnaro *et al.* (2010)
  Xiao *et al.* (2011); Knight *et al.* (2014)
1. Introduction

- Particle attrition in FINEX fluidized bed reduction reactor

- POSCO FINEX process
  - By using powdered iron ore without preprocessing, it could significantly reduce capital investment costs and pollutant emission
  - Use almost all particle size range

- In commercial scale, natural ore particles could be broken down by the high velocity of the distributor. (Werther and Xi, 1993; Xiao et al. (2011); Hao et al. (2015); Zhang et al. (2016)
2. Theory-1

• Attrition sources in fluidized beds

- A. Submerged jet attrition at the grid
- B. Bubble attrition
- C. Attrition in cyclones
- D. Attrition at valves of screw feeder
- E. Attrition at elbows
- F. Attrition in dilute-phase pneumatic conveying
- G. Free fall attrition

Main attrition source in fluidized bed
- Grid jets, bubbling fluidized bed, cyclones

Pell (1990); Yang (2003)

Fig. Sources of attrition in fluid bed systems; PSRI (2011)
2. Theory-2

• Particle attrition mode in fluidized beds

- Abrasion (surface abrasion, wear)
  - Removing the asperities at the particle surface
  - Abraded fines large amount of generation
  - No significant change in the particle size distribution
  - The particle shape goes to round form
  - Required less energy

- Fragmentation (breakage)
  - Broken into a number of parts in similar size
  - Increasing in the number of particles
  - Great change in the particle size distribution ($d_{sv}$)
  - Pointed out as a primary mechanism causing attrition
  - Required more energy

Fig. Attrition modes and their effects on particle size distribution; Yang (2003)
2. Theory-3

• Driving force of attrition at air jets

- **Impact force** has been pointed out as a major driving force in grid jet attrition caused by a *collision* when there bed material flow into the air jet area return to the fluidized bed
  - Bemrose and Bridgwater (1987)
  - Kutyavina and Baskakov (1972)
  - Choi *et al.* (2010)

- Inter-particle impact velocity in fluidized bed grid jet or spout bed is very high, so severe attritions were induced.

- If the bed height is lower than jet penetration length, attrition characteristics could not be easy to treat.

- At lower part of beds, fragmentation caused by fast particle collision by grid jet occurs
  - Vaux (1978)
2. Theory-4

- Previous study; kinetic energy rate from orifice - Werther and Xi model (1993)

- In range of jet velocity, $u_\text{or} < 100 \text{ m/s}$, the attrition rate was proportional to the cube of the jet velocity.

- In range of orifice diameter, $0.5 \text{ mm} < d_\text{or} < 2 \text{ mm}$, the attrition rate was proportional to the square of the orifice size.

- Thus, Werther and Xi suggested that the attrition model with kinetic energy rate could be determined as follows:

$$R_{\text{fine gen./time}} = K \rho_g d_\text{or}^2 u_\text{or}^3 \propto E_K$$

(Werther and Xi attrition model)

where $K$ [s$^2$/m$^2$] is attrition proportional constant, $\rho_g$ [kg/m$^3$] is gas density.
3. Objective

To investigate the attrition rate of iron ores by air jet with the variation of the kinetic energy rate from distributor
4. Experiment-1

• Apparatus (no circulation)

- Due to using 1 hole gas distributor, particles were inserted during aeration in order to prevent weeping

- Elutriation fines were accumulated or collected in the bag house and dipleg through the cyclone

Fig. Schematic diagram of the fluidized bed with no circulation
4. Experiment-2

• Apparatus and procedure (circulation)

1. Charging the hopper and the loopseal as follows
   - Bed inventory: 3.5 or 5.0 kg (-10 mm, sinter 100%)
   - Loopseal inventory: 2.5 kg (-250 μm, sinter 100%)

2. Starting the aeration and checking the circulation

3. Opening the valve of hopper (beginning)

4. Stop the aeration (end, after 30 mins)

5. Screening the all particles (6.0 or 7.5 kg) and then calculating the attrition rate
   - (bed, loopseal, bag house)

Fig. Schematic diagram of the fluidized bed with circulation
Riser diameter: 3 in = 0.075m, Height: 3.7 m
4. Experiment-3

• Apparatus (distributors)
  - Single hole distributors were used to prevent jet interactions.
  - Designing orifice nozzle diameter with air jet velocity, 113 m/s (nearly commercial nozzle velocity)

\[ \frac{\pi}{4} D_t^2 U_g = \frac{\pi}{4} d_{or}^2 u_{or} = Q \text{(volume flow rate)} \quad (D_t = 3\text{in}., d_{or}, u_{or} = 113\text{m/s}) \]

\[ \dot{m} = \rho_g A_{or} u_{or} = \rho_g \frac{\pi}{4} d_{or}^2 u_{or} = 0.0068 \text{ kg/s} \quad (\rho_g = 1.2 \text{ kg/m}^3) \]

\[ \therefore \dot{E}_k = \frac{1}{2} \dot{m} u_{or}^2 = 43 \text{ J/s} \]

- \( U_g = 1.2 \text{ m/s} \quad \Rightarrow \quad d_{or} = 0.0080m = 8.0 \text{ mm} \)
- \( U_g = 2.0 \text{ m/s} \quad \Rightarrow \quad d_{or} = 0.0101m = 10.1 \text{ mm} \)
- \( U_g = 2.5 \text{ m/s} \quad \Rightarrow \quad d_{or} = 0.0113m = 11.3 \text{ mm} \)
- \( U_g = 3.0 \text{ m/s} \quad \Rightarrow \quad d_{or} = 0.0124m = 12.4 \text{ mm} \)

Fig. Designed distributor (8, 10.1, 11.3, and 12.4 mm)
4. Experiment-4

- Experimental condition

Table: Kinetic energy rate from orifice with superficial gas velocity and distributor

<table>
<thead>
<tr>
<th>Condition</th>
<th>$U_g$ [m/s]</th>
<th>$u_{or}$ [m/s]</th>
<th>$d_{or}$ [mm]</th>
<th>$m_g$ [kg/s]</th>
<th>$E_K$ [J/s]</th>
<th>Time [min]</th>
<th>Mass basis [kg]</th>
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<td>0.0068</td>
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<td>8</td>
<td>0.0164</td>
<td>608.1</td>
<td>30</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Standard ASTM method:

- no circulation; $U_g=0.17$ m/s;
- $u_{or}=448$ m/s; $d_{or}=0.397$ mm;

$E_K = 6.7 \times 3 = 20.1$ J/s
4. Experiment-5

- Particles (fresh sinter feed of iron ore)

Table: Particle size distribution of bed materials (feed)

<table>
<thead>
<tr>
<th>Range [µm]</th>
<th>Average diameter [µm]</th>
<th>Fractional mass [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No circulation (3.5 kg basis)</td>
<td>Circulation (6.0 kg basis)</td>
</tr>
<tr>
<td>0 – 63</td>
<td>31.5</td>
<td>4</td>
</tr>
<tr>
<td>63 – 125</td>
<td>94</td>
<td>4</td>
</tr>
<tr>
<td>125 – 250</td>
<td>187.5</td>
<td>10</td>
</tr>
<tr>
<td>250 – 500</td>
<td>375</td>
<td>10</td>
</tr>
<tr>
<td>500 – 1000</td>
<td>750</td>
<td>10</td>
</tr>
<tr>
<td>1000 – 2800</td>
<td>1500</td>
<td>22</td>
</tr>
<tr>
<td>2800 – 4750</td>
<td>3000</td>
<td>18</td>
</tr>
<tr>
<td>4750 – 8000</td>
<td>6000</td>
<td>17</td>
</tr>
<tr>
<td>8000 – 9500</td>
<td>8750</td>
<td>5</td>
</tr>
<tr>
<td>(d_p)</td>
<td></td>
<td>357</td>
</tr>
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</table>

Fig. Fractional mass of bed materials

Table: Density of bed material

<table>
<thead>
<tr>
<th>Material</th>
<th>True density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter feed</td>
<td>3,705</td>
</tr>
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</table>
5. Result and Discussion-1

• Threshold size of attrition fine with no circulation

- Variation of particle size distributions before and after the experiment intersected at 500 μm in the severest condition \( U_g = 3.00 \text{ m/s}, \ u_{or} = 272.2 \text{ m/s}, \ E_k = 608 \text{ J/s}, \ 0.5 \text{ hour} \)

- It is reasonable to determine the threshold size of attrition fine as 500 μm.

---

Zenz and Kelleher (1980)

\[ y = (x_{after} - x_{before}) \]

\( x \): mass fraction
5. Result and Discussion-2

- Attrition trend with the kinetic energy rate

Attrition trends were not clear in the range $E_K < 180$ J/s.

Attrition rates increased with increasing the kinetic energy rate from orifice clearly in the range $E_K \geq 180$ J/s corresponded with Werther and Xi attrition model (1993)

$$\text{Degree of attrition} \% = \frac{\sum M_{d,p,\text{end}} - \sum M_{d,p,\text{ini}}}{M_{\text{ini}}} \cdot 100 = \sum (x_{d,p,\text{end}} - x_{d,p,\text{ini}}) \cdot 100$$

Ray and Jiang, 1987
5. Result and Discussion-3

• Variation of size distribution with no circulation ($E_K \geq 180$ J/s)

Fractional masses were varied with following regression lines during fixed 30 mins attrition time.

Zhang et al. (2016) reported that the attrition rates could be calculated by the variation of mother particle size distribution.

The error between y-intercept and y value were regarded as “initial attrition”.

The effect of “initial attrition” could be ignored.

Degree of attrition% = $\frac{\sum M_{d,p, end} - \sum M_{d,p, ini}}{M_{ini}} \cdot 100 = \sum (x_{d,p, end} - x_{d,p, ini}) \cdot 100$

Ray and Jiang (1987)
5. Result and Discussion-4

- Threshold size of attrition fine with circulation ($E_K \geq 180$ J/s)

![Graph showing variations in mass fraction before and after experiments for different particle diameter ranges and circulations.]

Fig. The differences of mass fraction between before and after experiments

- The particles less than 63 μm increased significantly unlike no circulation.
- It is reasonable that threshold size of attrition fines should be shifted to 63 μm.

---

Zenz and Kelleher (1980)

$$y = (x_{after} - x_{before})$$

$x$: mass fraction
5. Result and Discussion-5

- Experimental static bed height with theoretical jet length ($E_K \geq 180$ J/s)

Table Theoretical jet length and experimental bed heights in range of $E_K \geq 180$ J/s

<table>
<thead>
<tr>
<th>Condition</th>
<th>$U_g$ [m/s]</th>
<th>$u_{or}$ [m/s]</th>
<th>$d_{or}$ [mm]</th>
<th>$E_K$ [J/s]</th>
<th>Mass basis [kg]</th>
<th>Experimental static bed height* [cm]</th>
<th>Theoretical jet length [cm]</th>
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<td>181</td>
<td>8</td>
<td>180.2</td>
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<td>608.1</td>
<td>5.0 2.5</td>
<td>25.6</td>
<td>25.6</td>
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</tbody>
</table>

*: Experimental static bed heights were calculated by the bed weight after experiments

- At the ends of the each experiments, the bed heights should be higher than the each jet penetration lengths.
- Instead of the fluidized bed height, the static bed heights were compared with the jet lengths.
- According to Werther and Xi (1993), the attrition rates with higher bed heights than jet lengths were constant regardless of the bed inventory or the bed height.
5. Result and Discussion-6

- Attrition rates of iron ore with the kinetic energy rates

  - Attrition rates of iron ore increased with increasing the kinetic energy rates in the range $E_K \geq 180$ J/s.
  - Fragmentation dominant trends were observed entirely.
  - Werther and Xi (1993) attrition model was still valid in spite of occurring many fragmentations.
  - When the bed height was lower than jet length, the attrition rate did not follow the existing trend.

**Linear regression**

\[
\Phi/N = 0.1214E_K - 1.3587
\]

(180 J/s $\leq E_K \leq 608$ J/s)

where $N$ is the number of orifice[hole], $\Phi$ is the attrition rate [g/min].
6. Conclusion

1. Attrition rates of the iron ore with kinetic energy rate from orifice by varying the sizes of single orifice and the superficial gas velocity were investigated in the range $180 \text{ J/s} \leq E_K \leq 608 \text{ J/s}$.

2. The threshold size of attrition fines could be determined as “500 μm” with no circulation and “63 μm” with circulation.

3. With no circulation, the experimental range, $E_K \geq 180 \text{ J/s}$ which indicated the definite attrition trend was observed.

4. Werther and Xi (1993) attrition model was still valid in spite of occurring many fragmentations.

5. With circulation, the attrition correlation was obtained as $\Phi/N = 0.1214E_K - 1.3587$ in the given range.
Thank you for your attention.
Appendix

- Reference of CO2 capturing by limestone

  “Attrition characteristics and mechanisms for limestone particles in an air-jet apparatus”

  “The effect of CaO sintering on cyclic CO2 capture in energy system”
  ‘Limestone is widely used as a sorbent in fluidized beds, especially for SO2 and CO2 capture, because of its low price and wide availability.’

  “Sequential capture of CO2 and SO2 in a pressurized TGA simulating FBC conditions”

  “How does the concentration of CO2 affect its uptake by a synthetic ca-based solid sorbent?”

  “Capture of CO2 from combustion gases in a fluidized bed of CaO”
## Appendix (earlier studies)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Correlation</th>
<th>Variable</th>
<th>Etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forsythe and Hertwig, 1949</td>
<td>$R[%/hr] = \frac{(x_{fine \text{ after } 1h} - x_{fine \text{ at start}})}{(x_{non\text{fine} \text{ at start}})} \times 100$</td>
<td>Time: 1 h</td>
<td>FCC Fine threshold: 44, 40, 20 μm</td>
</tr>
<tr>
<td>Gwyn, 1969</td>
<td>$R[kg/h] = \frac{dW}{dt} = kn^t$</td>
<td></td>
<td>FCC</td>
</tr>
<tr>
<td>Haase et al., 1975</td>
<td>$R[%/hr] = \frac{(x_{fine \text{ after } 1h} - x_{fine \text{ at start}})}{(x_{non\text{fine} \text{ at start}})} \times 100 = k$</td>
<td>Time: 1 h</td>
<td>Fine threshold: 45 μm</td>
</tr>
<tr>
<td>Alcan International, 1982</td>
<td></td>
<td></td>
<td>No time-dependence</td>
</tr>
<tr>
<td>Lin et al., 1980, Kono, 1981</td>
<td></td>
<td></td>
<td>Iron ore (142-274 μm, 3940 kg/m³)</td>
</tr>
<tr>
<td>Chen et al., 1980</td>
<td>$R[kg/h] = CS \rho_g Q(Bu_{or})^2 \frac{Wd_p \rho_p}{\pi d_o^2}$</td>
<td>$u_{or}=25-300$ m/s</td>
<td>Silica-alumina FCC (106 μm, 1500 kg/m³)</td>
</tr>
<tr>
<td>Zenz and Kelleher, 1980</td>
<td>$R[kg/h] = C \left( u_{or} \sqrt{\rho_g} \right)^2 \pi d_o^2/4$</td>
<td>$u_{or}=33-303$ m/s</td>
<td>FCC</td>
</tr>
<tr>
<td>Werther and Xi, 1993</td>
<td>$R[kg/h] = C \rho_g d_o^2 u_{or}^3 \alpha E_K$</td>
<td>$u_{or}=25-100$ m/s</td>
<td>FCC</td>
</tr>
<tr>
<td>Ghadiri et al., 1994</td>
<td>$R[kg/h] = C d_o^n u_{or}^m$</td>
<td>$u_{or}=25-125$ m/s</td>
<td>FCC (425-600 μm), NaCl (90-106 μm)</td>
</tr>
<tr>
<td>McMillan et al., 2007</td>
<td>$\eta = 7.81 \times 10^{-7} \alpha \rho d_o 1.131 u_{or}^{0.55} \rho_g u_{or}^{2.1635} \left( u_g - u_{mf} \right)^{0.494}$</td>
<td>Grinding efficiency, $\eta [\text{m}^2/\text{kg}]$</td>
<td>Sonic nozzle</td>
</tr>
<tr>
<td>ASTM D5757, 2011</td>
<td>$R[%] = \frac{m_{fine \text{ after } 5h}}{m_{bed}} \times 100$</td>
<td>Time: 5 h</td>
<td>All elutriated fines</td>
</tr>
<tr>
<td>PSRI, 2011</td>
<td>$\Phi/N \left[ \frac{g}{\min \cdot \text{hole}} \right] = \frac{m_{fine}}{t \cdot N_{or}}$</td>
<td></td>
<td>Fine threshold: $d_p$</td>
</tr>
</tbody>
</table>