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

Dong Hyun Kang [a], Chang Kuk Ko [b], Dong Hyun Lee [a,*]

[a] *Department of Chemical Engineering, Sungkyunkwan University, Republic of Korea*
[b] *Ironmaking Research Group, Technical Research Laboratories, POSCO, Republic of Korea*

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ABSTRACT

The effects of superficial gas velocity ($U_g = 1.25–3.00$ m/s) and distributor hole size (8.0–12.4 mm) on the attrition rate of iron ore in a gas-solid fluidized bed with 0.076 m ID × 3.7 m height with or without solid circulation have been determined. The particle density and the Sauter mean diameter of fresh iron ore were 3705 kg/m^3 and 357 μm, respectively. When the kinetic energy rate from the orifice was equal or > 180 J/s, we could determine an attrition rate trend by measuring the fractional mass of fine particle formation (under 500 μm fraction) during 30 min without solids circulation. In the experiments with solids circulation, the attrition rate was determined by measuring the fractional mass of fine particle formation (under 63 μm fraction; variation of threshold size). The attrition rate increases with increasing kinetic energy rate from the orifice ($180\ \text{J/s} < E_K < 608\ \text{J/s}$). The kinetic energy rate from the orifice was calculated using the mass flow rate and orifice nozzle velocity. The correlation of the attrition rate with the kinetic energy rate from the orifice is $\Phi/N = 0.1214E_K - 1.3587$ above the jet length.

1. Introduction

Since fluidized bed reactors (FBRs) have several advantages such as rapid mixing, heat transfer, and large contact surface areas, these devices are used for a variety of processes; e.g., food, pharmaceuticals, petrochemicals, and energy production [1,2]. These benefits are generated by the contact between the bed particle and the fluidizing gas; however, serious attrition occurs due to surface frictions and collisions [3]. In commercial processes, it is difficult to ignore the effects of attrition on the quality of products, optimum operating conditions, reactant loss through elutriation, and equipment wear owing to long operation times and large scales. Particularly in catalysts, many researchers tried to increase the attrition durability of catalysts to augment their economic feasibility. Therefore, many studies of attrition of catalysts are limited [4–14]. Not only catalysts but also common bed materials could undergo attrition. However, few studies have been done on this subject. The attrition of limestone, which can be used as a sorbent of SO_2 and CO_2 in FBRs, is significant for the development of circulating fluidized bed combustors (CFBCs) and the integrated gasification combined cycle (IGCC) [15–19]. Thus, studies have been conducted on the attrition characteristics of limestone under the severe conditions of circulating fluidized beds [19–26]. Some processes involving reactions—such as combustion, reduction, oxidation, or pyrolysis—are improved by mechanical attrition due to the enlargement of the contact area, attrition rates can be controlled using supersonic nozzles [2]. In addition, the operating conditions of natural ores such as limestone are difficult to determine due to the wide particle size distributions (Geldart group C–D) and irregular shapes. Moreover, the optimum operating conditions could be slightly altered by breaking the particles under severe conditions. Therefore, attrition characteristics in fluidized beds should be studied to determine the degree of particle loss due to attrition. However, only few studies about the attrition rates of common bed materials using limestone are extant [15–19].

The types of attrition include particle fragmentation (breakage) and surface abrasion. Particles before attrition are termed mother particles (the matrix of particles) and those after attrition are termed attrition fines [19,20,25]. Fragmentation refers to the disintegration of mother particles of roughly similar sizes. Due to erratic particle disintegration, the size distribution is altered, the Sauter mean diameter decreases and there is an increase in the number of particles. In contrast, surface abrasion refers to grinding of sharp particles to produce attrition fines. Since ground sharp pieces are very small, the size distribution of mother particles remains unchanged [12,14,27].

The driving force of particle attrition is the collision between the bed materials or bed material and the inner wall of the main column [3,14]. As mechanical stresses act on a specific particle to be accelerated near the jet area, and then the accelerated particle would strongly collide with other particles or walls. The kinetic energy from the orifice is absorbed by the particle, causing severe attrition [28].

The major sources of attrition in fluidized beds are submerged grid jet attrition, bubbling attrition, and cyclone attrition [21]. When the air jet area which has low solid fraction is formed in the vicinity of the grid, the impact force among the particles accelerated by the air jet is the driving force of the submerged grid jet attrition [3,29,30].

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* Corresponding author.
E-mail address: dhlee@skku.edu (D.H. Lee).

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Table 1 shows the models available in the literature to calculate attrition rates, in particular for fluid catalytic cracking (FCC) [4–6,31,32,40]. Gwyn [5] suggested that the definition of attrition rate was (mass of fine loss) / (elapsed time), and then analyzed the attrition characteristics of FCC particles [6,26,31,32]. These results are valid only if all elutriated particles are formed by attrition, and the elutriation rate is higher than the attrition rate. Werther and Xi [6] reported that the attrition rates of FCC and HA-HPV particles were related with the fluidizing gas density, the square of the orifice diameter, and the cube of the orifice gas velocity, which was proportional to the kinetic energy rate of the gas from the orifice.

$$R = K\rho_g {d_{or}}^2 {u_{or}}^3 \qquad (\mathrm{K}\ [\mathrm{s}^2/\mathrm{m}^2]\ \text{depends on the material}) \tag{1}$$

However, the results are limited to mono-sized catalyst particles, and cannot be generalized to particles of a wide size range under severe conditions, such as $u_{or} > 100$ m/s. The attrition rate was determined for several hours because it is a function of time. Nevertheless, the short-term attrition rate is significant because of the high superficial gas velocity and short residence time in a fluidized bed with chemical reactions. To date, attrition was estimated using the standard ASTM D5757-method with a fixed kinetic energy rate. However, bed materials are typically fluidized under more severe conditions. With the exception of the fluidized bed attrition tests, jet cup attrition tests were conducted to analyze the properties of several materials [41–43].

Ray and Jiang [20] and Xiao et al. [19] reported that “initial attrition,” which is related to the removal of “fines adhering to the surface” and simple elutriation could be quantified by graphing the attrition rate with the Degree of Attrition.

Therefore, in this study, the effect of kinetic energy rate on attrition rate was determined using a variation of an air jet based on Eq. (1). The kinetic energy rate was controlled by the size of the orifice (8.0, 10.1, 11.3, and 12.4 mm) and the superficial gas velocity (1.2–3.0 m/s) in a laboratory-scale fluidized bed apparatus for 30 min. To determine the variation in the size distribution of iron ore, particles were screened after experiments. Single nozzle distributors were used to excluding jet interactions. In this study, the attrition rates of particles with wide size distribution have been determined under severe conditions simulating those used for industrial fluidized bed equipment.

2. Experimental

Table 2 shows the used particles, which are kinds of natural ore and had a size distribution ranging from 0 to 10 mm, as determined by sieving with the aid of a shaker. Three types of particles were prepared for experiments with or without solids circulation. The particles for without circulation experiments provided by the POSCO were iron ore (Australian iron, which has a broad size range of a very fine powder to 10 mm coarse particles). Circulation particles were almost the same as the particles for the experiments without circulation, but 2.5 kg of additional particles <250 μm in the loop-seal for solids circulation. The other particles for circulation experiments were composed of 5.0 kg of the bed and 2.5 kg of loop-seal, sieved to <250 μm. The size distribution of loop-seal particles is shown in Table 2.

Natural ores such as iron ores have fines adhering to the particle surfaces, which could be easily separated by a small impact [19]. Therefore, attrition rates should be calculated disregarding the fines adhering to the surface and the simple elutriation. The Sauter mean diameter and particle densities were 357 μm and 3705 kg/m^3, respectively. The sinter feed used in this experiment was heated for 24 h at 100 °C in an oven in order to evaporate all the water left in the damp iron concentrate.

Fig. 1 shows a schematic of the air jet attrition apparatus with and without solids circulation. The column was made of Plexiglas with a total height and diameter of 3.7 and 0.076 m, respectively. Distributors with a single nozzle size of 8.0, 10.1, 11.3, and 12.4 mm were used. Due to the large orifice diameters, the particles could be injected during aeration and a hopper was installed in order to prevent weeping. The attrition time was fixed at 30 min by opening the valve of the hopper. In the experiments without circulation, the elutriated particles were collected by a cyclone and a bag house over 30 min, and then all particles in the bed, the dipleg, and the bag were screened. In the circulation experiments, particle circulation was performed using an additional loop-seal, and then all particles in the bed, the loop-seal, and the bag were screened after 30 min.

The experimental conditions of superficial gas velocity and orifice diameter are summarized in Table 2. The calculations are based on Eqs. (2)–(4).

$$\mathrm{Q}(\text{gas volume flow rate}) = \frac{\pi}{4}\,\mathrm{D}_\mathrm{t}^2\,\mathrm{U_g} = \frac{\pi}{4}\,\mathrm{d}_\mathrm{or}^2\,\mathbf{u_{or}} \tag{2}$$

Table 1
Previous studies of attrition rates.

Authors	Correlation	Variables	Remarks
Forsythe and Hertwig, [4]	$R[\%/hr] = \frac{(x_{fine\ after\ 1h} - x_{fine\ at\ start})}{(x_{nonfine\ at\ start})} \times 100$	Time: 1 h	FCC Fine threshold: 44, 40, 20 μm
Gwyn, [5]	$R[kg/h] = \frac{dW}{dt} = knt^{n-1}$		FCC All elutriated fines
Haase et al., [35]	$R[\%/hr] = \frac{(x_{fine\ after\ 1h} - x_{fine\ at\ start})}{(x_{nonfine\ at\ start})} \times 100$	Time: 1 h	Fine threshold: 45 μm
Lin et al., [36] Kono, [37]	$R[\%/hr] = \frac{(x_{fine\ after\ 1h} - x_{fine\ at\ start})}{(x_{nonfine\ at\ start})} \times 100 = k$	No time-dependence	
Chen et al., [38]	$R[kg/h] = KS\frac{\rho_g Q(\beta u_{or})^2}{W d_P \rho_P}$	$u_{or} = 25\text{-}300$ m/s	Iron ore (142–274 μm, 3940 kg/m^3)
Zenz and Kelleher, [31]	$R[kg/h] = K(u_{or}\sqrt{\rho_g})^{2.5}\pi {d_{or}}^2/4$	$u_{or} = 33\text{–}303$ m/s	Silica-alumina FCC
Werther and Xi, [6]	$R[kg/h] = K\rho_g {d_{or}}^2 {u_{or}}^3 \propto E_K$	$u_{or} = 25\text{–}100$ m/s	FCC (106 μm, 1500 kg/m^3)
Ghadiri et al., [32]	$R[kg/h] = C{d_{or}}^n {u_{or}}^m$	$u_{or} = 25\text{–}125$ m/s FCC; $n = 0.6\text{-}0.76$, $m = 3.31$ NaCl; $n = 0.44\text{–}1.11$, $m = 5.1$	FCC (425–600 μm) NaCl (90–106 μm)
McMillan et al., [39]	$\eta = 7.81 \times 10^{-7}\alpha\beta {d_{or}}^{1.131} {u_{or}}^{0.55} (\rho_g {u_{or}}^2)^{1.635} (\frac{u_g - u_{mf}}{u_{mf}})^{0.494}$		Grinding efficiency, η[m^2/kg] Sonic nozzle
ASTM D5757, [40]	$R[\%] = \frac{m_{fine\ after\ 5h}}{m_{bed}} \times 100$	Time: 5 h	All elutriated fines
PSRI, [33]	$\Phi/N[\frac{g}{min \cdot hole}] = \frac{m_{fine}}{t \cdot N_{or}}$		Fine threshold: d_P
Asiedu-Boateng et al. [44]	$R = \beta_0(\frac{u_g - u_c}{u_s})^{\beta_1}(\frac{\rho_g}{\rho_{air}})^{\beta_2}(\frac{d_{or}}{0.39})^{\beta_3}$	Time: 6, 24, 96 h	u_c: attrition critical gas velocity above u_c, R depends on the pressure below u_c, R is independent of pressure

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