Particle Size Reduction Rate of Anthracite Ash by a Gas Jet

ARTICLE *in* INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH · FEBRUARY 2004

Impact Factor: 2.59 · DOI: 10.1021/ie0302903

Sang Done Kim
Korea Advanced Institute of Science and Tec…

GENERAL RESEARCH

Particle Size Reduction Rate of Anthracite Ash by a Gas Jet

See Hoon Lee[†] and Sang Done Kim*[,‡]

Gasification Application Research Center, Korea Institute of Energy Research, Daejeon 305-343, Korea, and Department of Chemical and Biomolecular Engineering and Energy & Environment Research Center, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea

The characteristics of particle size reduction of Korean anthracite ash (250−300, 300−425, 425−600, and 600−710 μm) by a gas jet in an ASTM attrition tester (D5757-95) with four different orifice sizes (0.38, 0.7, 1, and 1.5 mm) have been determined. The particle size reduction rates of anthracite ash were found to be a function of the operating parameters (superficial gas velocity, orifice gas velocity, bed weight) and the physical properties of the solid and gas phases (particle size and gas density). A simple model for particle size reduction rate based on the single-orifice attrition theory is proposed. The particle size reduction rate is proportional to the orifice velocity and gas density.

Introduction

Fluidized beds are widely used in various chemical and physical industrial processes because of the rapid solids mixing, good heat transfer, and excellent isothermal conditions throughout the reactor. Fluidized-bed combustors are especially widely used because they can handle various fuels. However, fluidizing gas often leads to jet formation, which causes intense interparticle collisions to break fluidizing particles during operation. Also, fluidization might change the particle size distribution and the hydrodynamics in the bed, and fine particles resulting from jet attrition might finally be collected by the dust recovery system, consequently leading to a loss of bed materials.[1−3] Particle attrition in the jetting region contributes to a significant extent to the overall particle attrition in a fluidized bed.[4] Also, catalyst attrition resistance is one of the major design criteria in catalyst development.[5]

Particle attrition in fluidized beds was initially studied by Forsythe and Hertwig[6] to characterize catalyst attrition of a FCC (fluid-catalytic-cracking) process. Several researchers have proposed different attrition mechanisms, such as bubbles in various fluidized beds[7−9] and attrition by grid jet.[1,4,5,10,11] Among the methods developed for evaluating the resistance of a catalyst to attrition, the fluidized-bed test (also called the air-jet test) is commonly used.[5] Particle attrition by a gas jet in a fluidized bed with a single orifice was studied by Werther and Xi[10] and Wu et al.,[11] and attrition of a granular slug by a single horizontal jet installed in a fluidized bed was investigated by Kage et al.[12] However, studies on the reduction of the particle size in a fluidized bed are relatively sparse compared to the studies on fine particle generation due to attrition.

Therefore, the effects of the superficial gas velocity (U_g), in terms of the orifice gas velocity (U_{or}); the initial bed weight or height; the jet length; and the physical properties of the particle diameter and gas density on the jet attrition and the size reduction of the particles have been determined in the commonly used fluidized bed tester (ASTM D5757-95 attrition tester). Also, a model of the particle size reduction rate based on the Werther and Xi attrition theory has been proposed.[10]

Theory

Werther and Xi[10] proposed the single-orifice attrition model using the relation between the surface energy of the bed materials and the kinetic energies of the input gases. A gas jet having an orifice velocity of $U_{or,s}$ into the bed through a perforated plate will produce a kinetic energy (P_j) per unit time of

$$P_j = \frac{\dot{m}}{2}U_{or,s}^{\ 2} = \frac{1}{2}\rho_g Q U_{or,s}^{\ 2} \quad (1)$$

where m, $U_{or,s}$, ρ_g, and Q are the mass flow rate into the bed, the single-orifice velocity, the gas velocity, and the volumetric gas flow rate, respectively. If there is no interaction between the individual jets, the entire attrition in the jet region can be interpreted as a sum of the contributions of the individual jets.[1] Then, the input kinetic energy for multiple orifices can be expressed as

$$P_j = \frac{\dot{m}}{2}U_{or}^{\ 2} = \frac{1}{2}\rho_g Q U_{or}^{\ 2} = \frac{1}{2}\rho_g \frac{\pi}{4} n_{or} d_{or}^{\ 2} U_{or}^{\ 3} \quad (2)$$

where n_{or} and d_{or} are the number of orifices and the orifice diameter, respectively.

Because the collision of particles due to the gas jet causes abrasion of the particle surfaces, Werther and Xi[10] considered the efficiency of energy consumption of the attrition process. They assumed that the surface energy of the attrite fines would be roughly equal to the

* To whom correspondence should be addressed. Tel.: 82-42-869-3913. Fax: 82-42-869-3910. E-mail: kimsd@kaist.ac.kr.
† Korea Institute for Energy Research.
‡ Korea Advanced Institute of Science and Technology.

10.1021/ie0302903 CCC: $27.50
Published on Web 01/22/2004

newly created surface area as

$$E_f = nS_i\gamma \qquad (3)$$

where S_i is the mean surface area of an individual particle and γ is the specific surface energy. They also assumed that the surface energy of the newly created particles would be the difference between the surface energy before and after the operations in the bed, i.e.

$$E_f = E_o - E_a = (n_oS_o - n_aS_a)\gamma \qquad (4)$$

Abrasion produces a great deal of very fine material removed from the surface of the initial particles, which retain their identity and become only slightly smaller.[1] If this assumption is valid for a fine-particle system, it can be assumed that number of particles remains unchanged as jet attrition would be merely an abrasion process. Therefore, eq 4 above becomes

$$E_f = E_o - E_a = n_o\gamma(S_o - S_a) \qquad (5)$$

The number of particles (n_o) in the given bed diameter depends on the initial bed weight and can be expressed as

$$n_o = \frac{W_o}{w_s} = \frac{\rho_b\frac{1}{4}\pi d_t^{\,2}L}{\rho_s v_s} = \frac{\rho_b\frac{1}{4}\pi d_t^{\,3}}{\rho_s v_s}\frac{L}{d_t} = C_n\frac{L}{d_t} \qquad (6)$$

where d_t, L, v_s, W_o, ρ_b, ρ_s, and C_n are the bed diameter, bed height, volume of a single particle, initial solid weight, bulk density of the particles, density of a single particle, and number of particles (which is constant), respectively.

Werther and Xi[10] proposed an efficiency factor (α) that was related to the surface energy caused by gas-jet attrition due to the kinetic energy (E) dissipated into the bed as

$$\alpha = \frac{E_f}{P_j\Delta t} \qquad (7)$$

Introducing eqs 2, 5, and 6 into eq 7 yields

$$\frac{(S_o - S_a)}{\Delta t} = \frac{\alpha\pi}{8C_n\gamma}n_{or}\rho_g\left(\frac{d_t}{L}\right)d_{or}^{\,2}U_{or}^{\,3} \qquad (8)$$

Therefore, the particle size reduction rate due to gas-jet attrition can be written as

$$S_j = \frac{1 - \left(\frac{d_a}{d_o}\right)^2}{\Delta t} = \frac{\alpha}{8C_n\gamma}n_{or}\rho_g\left(\frac{d_t}{L}\right)\left(\frac{d_{or}}{d_o}\right)^2U_{or}^{\,3} = K_sn_{or}\rho_g\left(\frac{d_t}{L}\right)\left(\frac{d_{or}}{d_o}\right)^2U_{or}^{\,3} \qquad (9)$$

where the size reduction constant, K_s, describes the material property, such as the attrition constant, that can be influenced by the employed particles.

Experimental Section

A fluidized bed (Figure 1) was designed according to the specifications for the attrition tester (attrition tube, 0.035-m i.d. × 0.71-m height; settling chamber, 0.11-m i.d. × 0.3-m height) of the American Standard Testing Materials (ASTM-D 5757-95). A perforated-plate gas distributor containing three orifices (0.381 mm with a triangular pitch of 0.017 m) was attached at the bottom of the reactor. Fine particles generated by a gas jet were collected in a triangular flask with a thimble filter (28 × 100 mm, Advantec Co.). The standard test conditions of the ASTM D5757-95 tester are a volumetric flow rate of air of 10 L/min (U_g = 0.17 m/s, U_{or} = 487 m/s), a sample weight of 50 g, and an operation time of 5 h.

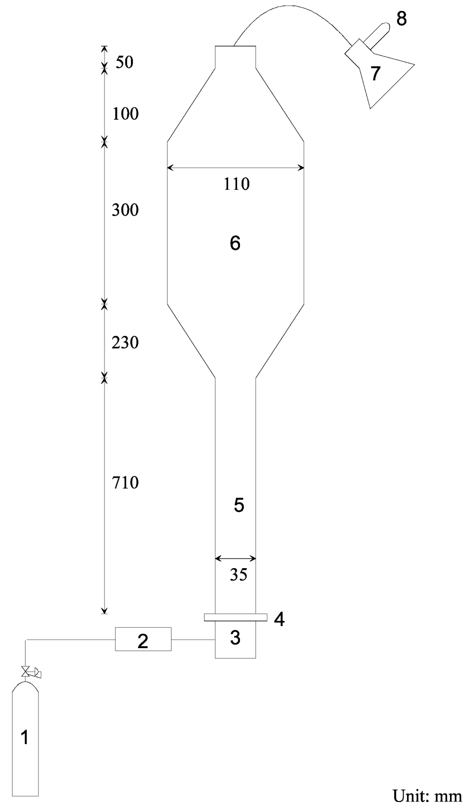

Figure 1. Schematic diagram of a jet attrition tester: 1, air; 2, MFC; 3, windbox; 4, distributor; 5, attrition tube; 6, settling chamber; 7, triangular flask; 8, thimble filter.

To determine the effects of the orifice size on the particle size reduction due to jet attrition, three different perforated plates (orifice sizes of 0.7, 1.0, and 1.5 mm with a triangular pitch of 0.017m) were employed. To determine the effects of the orifice gas velocity in terms of the superficial gas velocity, the superficial gas velocity were varied from 0.09 to 0.40 m/s (volumetric flow rate of 5−23 L/min), as regulated by a mass flow controller (5850EM, Brooks Co.).

The orifice gas velocity is calculated according to

$$Q = \frac{\pi}{4}d_t^{\,2}U_g = \frac{\pi}{4}n_{or}d_{or}^{\,2}U_{or} \qquad (10)$$

Because the standard sample weight in the ASTM D5757-95 tester is 50 g, the sample weight was varied from 30 to 100 g to determine the effect of the initial bed weight or height. The operation time of all of the experiments was 5 h, in accordance with the ASTM D5757-95 method. The bed material was Korean anthracite ash with an apparent density of 1.7 g/cm^3. The ash sizes were 250−300, 300−425, 425−600, and 600−710 μm, and the ash analysis data are reported in Tables 1 and 2.

For each run of the experiment, samples of fine ash were taken at steady state from the triangular flask

Table 1. Composition of the Ash

component	content (wt %)
SiO_2	53.17
Al_2O_3	33.77
Fe_2O_3	4.43
CaO	0.70
MgO	0.76
K_2O	4.19

Table 2. Properties of the Particles

sieve size	mean size (μm)	U_{mf}[a] (m/s)	U_t[b] (m/s)
250−300	260	0.03	1.27
300−425	325	0.08	2.16
425−600	513	0.19	3.38
600−710	655	0.28	4.14

[a] Calculated by Chitester et al.[13] [b] Calculated by Haider and Levenspiel.[14]

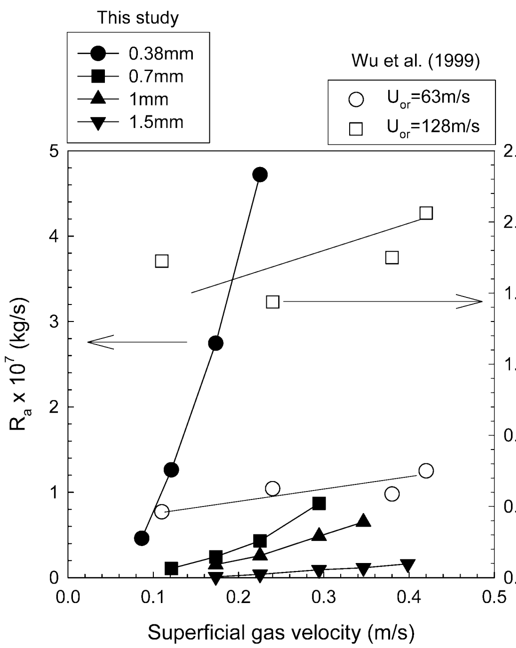

Figure 2. Effect of the superficial gas velocity on the attrition rate.

with a thimble filter for every 1-h time period. The attrition rate is commonly defined by the relative weight change of the bed material with time or, alternatively, by the relative change in elutriated fines with the square of time, as in the present study. After each experimental run, the particle size distribution and the mean particle size of the ash in the bed were determined by sieving the samples (0−106, 106−150, 150−212, 212−250, 250−300, 300−425, 425−600, and 600−710 μm).

Results and Discussion

1. Effects of Operating Parameters. The effect of the superficial gas velocity (U_g) on the attrition rate of the ash (d = 300 − 425 μm, W = 0.05 kg) caused by a gas jet is shown in Figure 2. As can be seen, the attrition rate increases with increasing superficial gas velocity (U_g), as reported in previous studies.[6−9] The particle velocity is directly related to the gas velocity, which is the most important factor affecting attrition if particle degradation occurs as a result of mechanical stress due to interparticle collisions or collisions between the particles and a solid wall.[1,10] With a single orifice in a fluidized bed,[11] the attrition rate was found to increase with increasing U_g at the same orifice velocity. In contrast, Kage et al.[12] reported that the effect of U_g on particle attrition can be neglected in a rectangular fluidized bed with a single horizontal nozzle above the distributor.

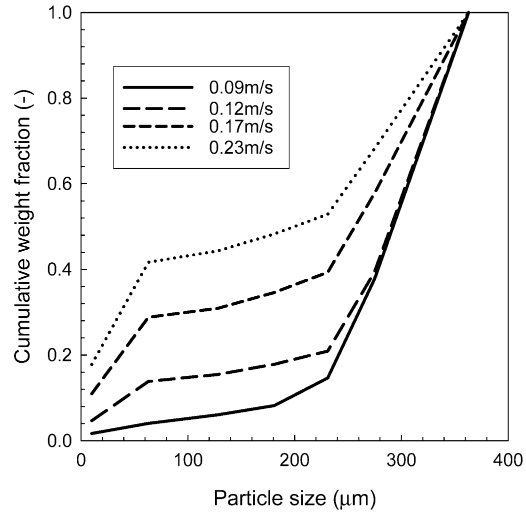

Figure 3. Effect of the superficial gas velocity on the particle size reduction.

The size distributions of the residual bed material and the fine particles collected in a triangular flask with a thimble filter after the operation are shown in Figure 3 (d_{or} = 0.38 mm, d = 300−425 μm). As can be seen, the weight fractions under 100 μm increase with increasing U_g as a result of of the attrition of the bed material. The attrited bed material produces extra fines that are perferentially elutriated if their terminal velocity is lower than the operating superficial velocity in the bed or freeboard.[11] Generally, the abrasion of particles produces very fine powders from the surface of the initial particles, which retain their identity and become slightly smaller in size.[1,10] However, more fine powders are produce with increasing U_g, so that the weight of the original particles decreases (d = 300−425 μm). As a result, the mean particle size is reduced to 240 μm, which that indicates the abrasion process due to the gas jet severely changes the particle size distribution in the bed.

The effect of U_g on the size reduction rate after 5 h of operation is shown in Figure 4. As can be seen, the particle size reduciton rate increases with increasing U_g with the different gas distributors. Because increasing U_g leads to an increase in the kinetic energy of the gas phase and particle elutriation, particles accelerated by a gas jet that might provide more intense particle collisions and a consequent increase in particle attrition.[10−12] As can be seen in Figure 3, the type of jet attrition occurring in anthracite ash might be an abrasion process, and the model predicts the particle size reduction rate well in comparison with the experimental data.

The effect of the orifice gas velocity (U_{or}) on the attrition rate is shown in Figure 5, where the attrition rate is seen to increase with increasing U_{or}. A gas jet issuing from an orifice into a fluidized bed produces input kinetic energy that accelerates particles to collide with other particles.[10] Werther and Xi[10] and Werther and Reppenhagen[1] reported that the grid-jet attrition rate is proportional to the cube of jet velocity and that

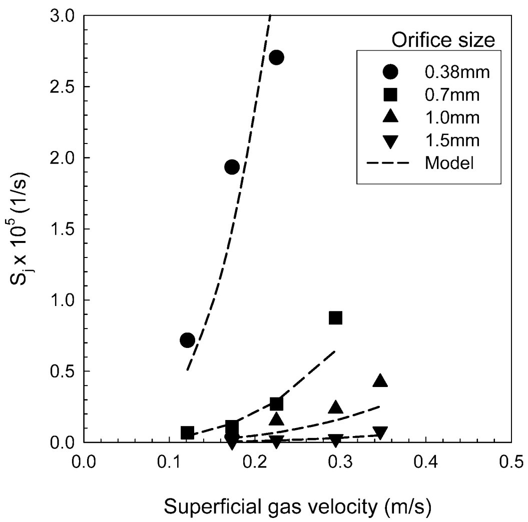

Figure 4. Particle size distributions after 5 h of operation at different gas velocities.

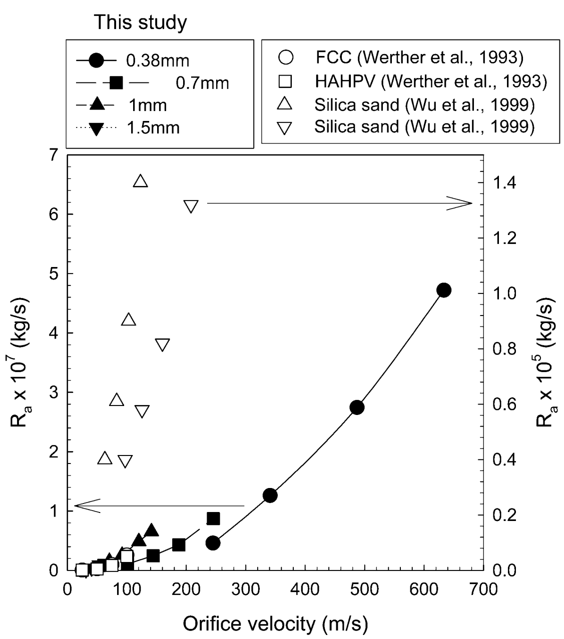

Figure 5. Effect of the orifice gas velocity on the attrition rate.

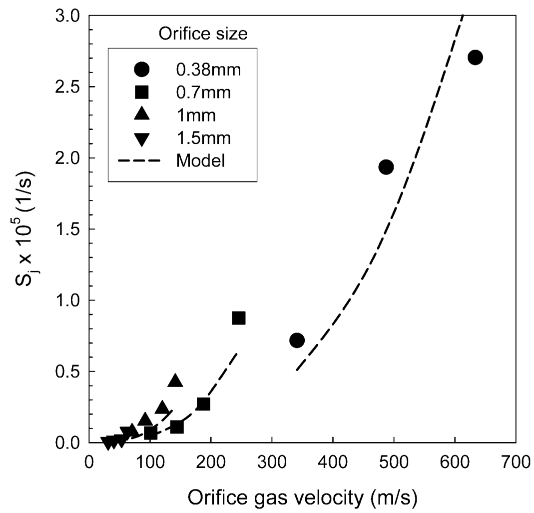

Figure 6. Effect of the orifice gas velocity on the particle size reduction.

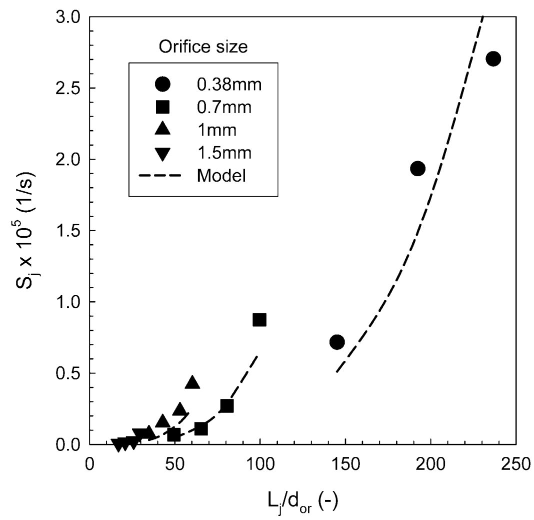

Figure 7. Effect of the jet length (L_j/d_{or}) on the particle size reduction.

it increases with increasing jet velocity. Chariri et al.[4] reported that the effect of the orifice gas velocity on the particle attrition rate can be related to the bed hydrodynamics and particle impact characteristics. Also, it has been reported that the attrition coefficient is strongly related to the jet velocity in an experiment with a single horizontal jet.[12]

The effect of the orifice velocity (U_{or}) with different distributors on the size reduction rate of anthracite ash after 5 h of operation is shown in Figure 6 for particle sizes ranging from 300 to 425 μm. The particle size reduction rate increases with increasing U_{or} as a result of increasing particle attrition. Even if the orfice velocity is the same, the partice size reduction rate is different because of the difference in the elutriation of the ash particles. Also, it has been reported that the mean particle size due to jet attrition decreases with increasing particle sphericity.[12,15,16]

The particle size reduction caused by a gas jet might be a function of the jet length as the gas jet affects only a limited bed volume above the gas distributor.[1] The effect of the jet length on the particle size reduction rate of the anthracite ash is shown in Figure 7, where jet lengths were obtained from the correlation of Yates et al.[17] The particle size reduction rate due to particle attrition increases with increasing jet length. Because of the limited volume of the bed material from the distributor affected by gas jet, particle size reduction rate increases with increasing jet penetration length. The contribution of the jet penetration length to the particle attrition remains constant with a further increase in the bed height as soon as the jet is fully submerged in the bed.[1]

The effect of the initial bed height or weight on the particle size reduction rate is shown in Figure 8, where the results for two different orifice sizes (0.38 and 0.7 mm) and two gas velocities (0.17 and 0.23 m/s) are displayed. As can be seen, the particle size reduction rate decreases with increasing initial bed height for an orifice size of 0.38 mm. For an orifice size of 0.7 mm, the particle size reduction rate decreases marginally with initial bed height because of the lower orifice gas velocities. The presented model underestimates the particle size reduction with the 0.38-mm orifice, but it predicts very well the results for the 0.7-mm orifice. The progression of attrition might decrease because the bed volume is unaffected by the gas jet, and consequently,

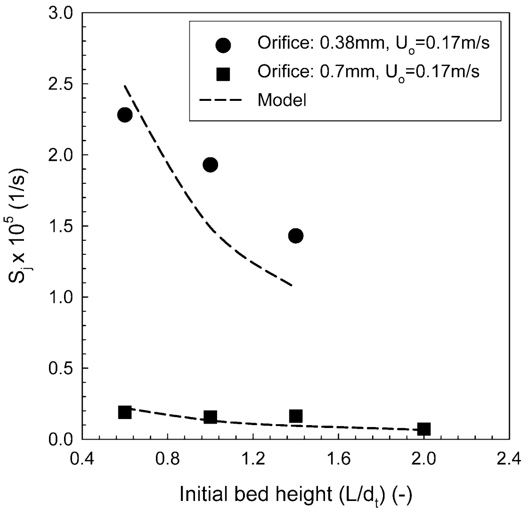

Figure 8. Effect of the initial bed height (L/d_t) on the particle size reduction.

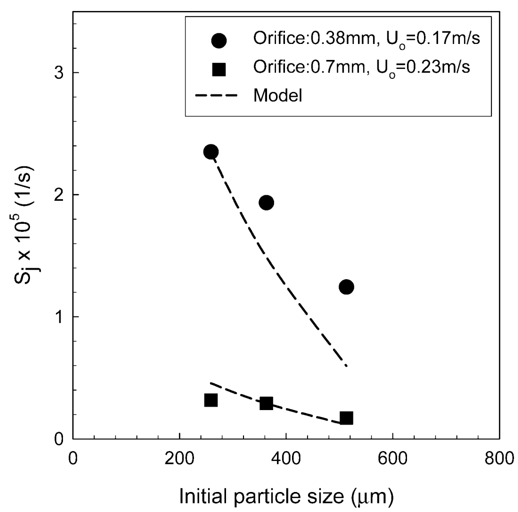

Figure 9. Effect of the mean particle size on the particle size reduction.

the size reduction rate might decrease with increasing initial bed height or weight. However, the attrition rate does not change appreicably at 8.63 × 10^{-4} kg/h. In contrast, in bubbling and slugging beds,[18,19] the attrition rate increases with increasing bed height as a result of more intense particle mixing caused by larger bubbles and slugs in the bed.

2. Effects of Physical Properties. If the particle size distribution changes, the minimum fluidizing and terminal velocities of the particles will also change. The particle size and particle properties have a strong effect on the attrition rate in the jetting region.[4] The effect of the initial particle size on the particle size reduction rate after 5 h of operation is shown in Figure 9. The size distributions of ash used were 250−300, 300−425, and 425−600 μm. The particle size reduction rate decreases with increasing initial particle size because of the decrease in particle velocity and consequent decrease in the attrition rate. A shift of the particle size distribution to a smaller particle size range might lead to an increase in fine particle production due to abrasion.[2] The presented model underestimates the effect of the intitial particle size on the size reduction rate with increasing particle size because coarse particles tend to fragment more than abrade.

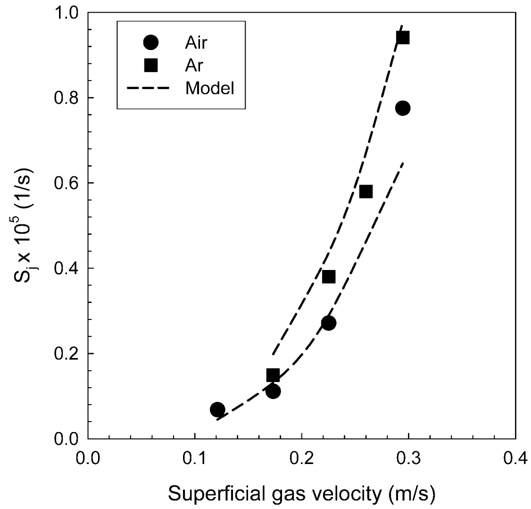

Figure 10. Effect of the superficial gas velocity on the particle size reduction using Ar gas.

The gas density might influence the jet penetration length, which might, in turn, influence the particle attrition or particle size reduction.[1] The effect of the superficial gas velocity on the particle size reduction rate for different gas densities is shown in Figure 10 in which the orifice size was 0.7 mm and the particles size range was 300−425 μm. The particle size reduction rate increases with increasing gas velocity regardless of the gas density. However, the reduction rate is somewhat higher with Ar gas than with air because the jet penetration length of Ar is longer and the input kinetic energy is higher than those of air.

The proposed model can predict the particle size reduction rate well, as the model takes into account the effects of the orifice size, gas velocity, gas density, and aspect ratio of the tester. Using model eq 9, the K_s value was correlated with the present experimental data, and it was found that $K_s = 2.66 \times 10^{-14}$ with a correlation coefficient of 0.90.

Conclusions

The effects of the operating and physical parameters on the reduction of the mean particle size of Korean anthracite ash have been determined in an attrition tester (ASTM D5757-95). The particle size reduction rate increases with increasing superficial gas velocity in terms of the orifice gas velocity and gas density, but it decreases with increasing initial bed height or weight. A simple model based on single-orifice attrition theory was proposed to take into account the effects of the orifice size, gas velocity, gas density, and aspect ratio of the bed on the particle size reduction due to gas-jet attrition.

Acknowledgment

We acknowledge a grant-in-aid for research to S.D.K. from the Ministry of Commerce, Industry and Energy, Korea, and the Korea Electric Power Research Institute.

List of Symbols

C_n = number of particle (constant)
d = mean particle size (m)
d_i = mean particle size of the ith size range (m)
d_a = mean particle size after attrition (m)
d_o = mean particle size before attrition (m)

d_{or} = orifice diameter (m)
d_t = bed diameter (m)
E_f = total surface energy of attrited fines (J)
E_a = total surface energy of particles after attrition (J)
E_o = total surface energy of original particles before attrition (J)
K_s = size reduction constant (kg/s^3)
L = bed height (m)
L_j = jet length (m)
$\dot{m}$ = mass flow rate into the bed (kg/s)
n = number of particles
n_{or} = number of orifices
n_a = number of particles after attrition
n_o = number of particles before attrition
P_j = kinetic energy input by the gas jet per unit of time (J/s)
Q = volumetric flow rate (m^3/s)
R_a = attrition rate (kg/s)
S = mean surface area of an individual particle (m^2)
S_a = mean surface area of an individual particle after attrition (m^2)
S_o = mean surface area of an individual particle before attrition (m^2)
S_j = particle size reduction (1/s)
t = time (s)
U_g = superficial gas velocity (m/s)
U_{or} = orifice gas velocity in a distributor with multiple orifices (m/s)
$U_{or,s}$ = single-orifice gas velocity (m/s)
v_s = volume of a single particle (m^3)
W = bed weight (kg)
w_s = weight of a single particle (kg)
x_i = weight fraction of the ith size range

Greek Letters

α = energy efficiency factor
γ = specific surface energy (J/m^2)
ρ_b = bulk density of the particles (kg/m^3)
ρ_g = gas density (kg/m^3)
ρ_s = density of a single particle (kg/m^3)

Literature Cited

(1) Werther, J.; Reppenhagen, J. Attrition in fluidized beds and pneumatic conveying lines. In *Fluidization Solids Handling and Processing*; Yang, W.-C., Ed.; Siemens Westinghouse Power Corporation: Pittsburgh, PA, 1999; p 435.

(2) Werther, J.; Reppenhagen, J. Catalyst attrition in fluidized-bed systems. *AIChE J.* **1999**, *45*, 2001.

(3) Lee, S. H.; Kim, S. D.; Lee, D. H. Particle size reduction of anthracite coals during devolatilization in a thermobalance reactor. *Fuel* **2002**, *81*, 1633.

(4) Ghadiri, M.; Cleaver, J. A. S.; Tuponogov, V. G.; Werther, J. Attrition of FCC powder in the jetting region of a fluidized bed. *Powder Technol.* **1994**, *80*, 175.

(5) Zhao, R.; Goodwin, J. G.; Jothimurugesan, K.; Spivey, J. J.; Gangwal, S. K. Comparison of Attrition Test Methods: ASTM Standard Fluidized Bed vs Jet Cup. *Ind. Eng. Chem. Res.* **2000**, *39*, 1155.

(6) Forsythe, W. L.; Hertwig, W. R. Attrition Characteristics of Fluid Cracking Catalysts. *Ind. Eng. Chem.* **1949**, *41*, 1200.

(7) Merrick, D.; Highley, J. Particle size reduction and elutriation in a fluidized bed process. *AIChE Symp. Ser.* **1974**, *70*, 366.

(8) Arena, U.; D'amore, M.; Massimilla, L. Carbon attrition during the fluidized combustion of a coal. *AIChE J.* **1983**, *29*, 40.

(9) Ray, Y. C.; Jiang, T. S.; Wen, C. Y. Particle attrition phenomena in a fluidized bed. *Powder Technol.* **1987**, *49*, 193.

(10) Werther, J.; Xi, W. Jet attrition of catalyst particles in gas fluidized beds. *Powder Technol.* **1993**, *76*, 39.

(11) Wu, S. Y.; Baeyens, J.; Chu, C. Y. Effect of the grid velocity on attrition in gas fluidized beds. *Can. J. Chem. Eng.* **1999**, *77*, 738.

(12) Kage, H.; Kawaji, K.; Ogura, H.; Matsuno, Y. Attrition of granular slug by single horizontal jet equipped in fluidized bed. *J. Chem. Eng. Jpn.* **2000**, *33*, 605.

(13) Chitester, D. C.; Kornosky, R. M.; Fan, L. S.; Danko, J. P. Characteristics of fluidization at high pressure. *Chem. Eng. Sci.* **1984**, *39*, 253.

(14) Haider, A.; Levenspiel, O. Drag coefficient and terminal velocity of spherical and nonspherical particles. *Powder Technol.* **1989**, *58*, 63.

(15) Gwyn, J. E. On the particle size distribution function and the attrition of cracking catalysts. *AIChE J.* **1969**, *15*, 35.

(16) Kono, H. Attrition rates relatively coarse solid particles in various types of fluidized beds. *AIChE Symp. Ser.* **1981**, *77*, 96.

(17) Yates, J. G.; Rowe, P. N.; Cheesman, D. J. Gas entry effects in fluidized bed reactors. *AIChE J.* **1984**, *30*, 890.

(18) Seville, J. P. K.; Mullier, M. A.; Adams, M. J. Attrition of agglomerates in fluidized bed. *Fluidization VII*; Potter, O. E., Nicklin, D. J., Eds.; Engineering Foundation: New York, 1992; p 587.

(19) Ghadiri, M.; Cleaver, J. A. S.; Yuregir, K. R. Attrition of sodium chloride crystals in a fluidized bed. *Fluidization VII*; Potter, O. E., Nicklin, D. J., Eds.; Engineering Foundation: New York, 1992; p 603.

Received for review April 10, 2003
Revised manuscript received December 12, 2003
Accepted December 12, 2003

IE0302903