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Attrition of Coal Ash Particles in a Fluidized-Bed Reactor

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Experimental data of ash-particles attrition in a fluidized bed is presented, and also the results of modeling. Five sizes of ash particles (1.02-:-1.25; 1.25-:-1.6; 1.6-:-2.0; 2.0-:-5.0; 5.0-:-10.0 mm) produced in an industrial CFB boiler were examined. A new model of mechanical attrition has been proposed which incorporates new parameters: the shape factor of particles and the ratio of the bed height to bed diameter, strongly influencing the rate of bed mass loss. The model describes very well experimental data for coal-ash particles attrition. The attrition-rate coefficient for ash particles was evaluated. © 2007 American Institute of Chemical Engineers *AIChE J,* 53: 1159–1163, 2007
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Introduction

The size of particles within a fluidized-bed combustor is an important parameter determining the bed structure and the intensity of heat transfer to the cooling surfaces.[1] The feeding solids contain fuel particles (formed of organic and mineral particles), and the flue-gas desulfurizing sorbent. In consequence of the fast combustion process of organic particles the bed is formed in over 90% of fluidizing mineral particles (transformed at high-temperature into ash), and the sorbent particles. The size of these grains differs much from that at feeding, because of the attrition during long-residence time in the bed. A proper understanding of the particles mechanical attrition mechanism, and their attrition properties are helpful during the designing process.

The aim of this research was to introduce a particle rounding up phenomenon into a mathematical model, describing the rate of coal-ash particles attrition in a fluidized bed. Six size groups of ash grains were examined during experiments lasting up to 28 h for each group. It has been found that the shape of particles and the bed geometry strongly influenced the rate of attrition, besides the two commonly considered parameters: mass of particles in the bed and the apparent fluidization velocity. A new model of attrition has been proposed, which describes well the observed evidence of own experiments. The attrition coefficient for ash particles was found.

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State of art

Mutual collisions of particles in a fluidized bed, as well as particles collisions with the reactor walls are the main reasons of mechanical attrition, which lead to particles-size reduction and their shape variation. The proposed mathematical models are not able to describe the observed attrition process in long-time intervals. Different material of grains used by investigators make the comparison of models difficult.[2–5] The common assumption in all these models is that fines which tear off from the grains during the attrition, instantly elutriate from the bed. A reliable mathematical model of the attrition phenomenon should enable calculation of grain-size distribution, within the bed on the basis of balance equations of grain-size groups.[7] A relation between the feeding solids and the physical and chemical processes within a fluidized-bed combustor can then be found.

The rate of particles mechanical attrition is described by a general equation[8]

$$\frac{dm}{dt} = -K_{\mathrm{a}}m, \tag{1}$$

where the definition of the attrition coefficient K_{a} in s^{-1} units, distinguishes the known models. Merrick and Highley[2]

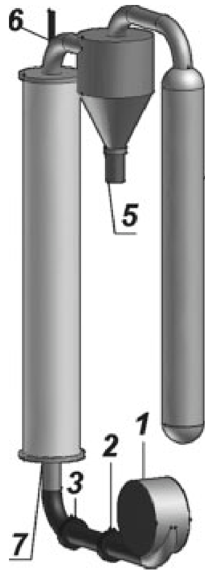

Figure 1. Experimental unit: (1) fan, (2) gas stream valve, (3) orifice, (4) bag filter, (5) cyclone separator, (6) particles feeding valve, and (7) solids removal point.

proposed a linear relation between the attrition coefficient and the apparent fluidization velocity, and determined its value for ash and hard coal particles on the basis of bubbling-fluidized bed experiments. Arena et al.[3] assuming that the reduction of particles size is a result of a surface phenomenon, came to conclusion that the attrition coefficient is inversely proportional to particle diameter. They found its value on basis of fluidized-bed experiments in which combustion of hard coal took place, while quartz sand particles were used as an inert material. Lee et al.[4] considered that the attrition rate of particles within a circulating fluidized bed decreases with time, and at the bed mass $m_{\min}$ becomes negligible. They proposed a modification of Eq. 1 into a form

$$\frac{dm}{dt} = -K_a(m - m_{\min}), \tag{2}$$

in which the attrition coefficient of CaO particles was found on basis of circulating fluidized-bed experiments. Cook et al.[5] after attrition tests of CaO in a circulating fluidized bed, came to the conclusion that the concept of $m_{\min}$ of the bed mass is justified, but the term in the brackets of Eq. 2 has to be replaced by a form ($m^2 - m^2_{\min}$). However, the titles of the articles[4,5] mention attrition experiments in circulating beds, but as a matter of fact were conducted in stationary fluidized beds, because the recirculation valve was closed.[5]

All the earlier models neglect the changes of particles shape during the attrition tests, what is more this important parameter was not identified during these experiments. Already the initial tests during our research have shown that the attrition of particles follow the mode observed before by Lee et al.:[4] as the grains become smaller with time they loose sharp edges and become more spherical. Also Scala et al.[6] conducting attrition experiments of sorbents during fluidized-bed calcinations and sulfation noticed rounding off the particle surface. We have decided then to measure not only the bed mass loss during experimental time, but also the variation of particles size and their shape factor. What is more, we have noticed also that the geometry of the fluidized bed expressed as the ratio of the stationary bed height to the effective reactor diameter is also an important parameter influencing the attrition rate.

Experimental

Experiments were conducted in a fluidized-bed reactor presented in Figure 1. Ash particles of size distribution given in Figure 2, were obtained from the bottom part of an industrial fluidized boiler burning subbituminous Silesian coal. Before experiments the ash sample was sieved, so that six size fractions were produced. Table 1 presents the reactor geometry and the main experimental parameters. The shape factor of particles has been determined on the basis of a pressure drop Δp of air flowing through a layer of particles in a reactor made of perspex. The Kozeny[9] and Carman[10] equations were used for pressure drop relation

$$\Delta p = \lambda_f \rho_g \frac{w^2}{2} \frac{H_0}{d_p} f(\varepsilon, \varphi), \tag{3}$$

where the function $f(\varepsilon,\varphi)$ according to Leva[11] has a from

$$f(\varepsilon, \varphi) = \frac{(1-\varepsilon)^{3-n}}{\varepsilon^3} \varphi^{3-n}, \tag{4}$$

and for $Re \in (1\text{-:-}10^4)$ the factor n was found $n = 0.95 + \exp(-33/Re)$. For the experimental range of the Reynolds number $Re \in (25\text{-:-}2300)$ the friction factor is described by the Ergun equation[12]

$$\lambda_f = 1.75 + \frac{150(1-\varepsilon)}{Re}. \tag{5}$$

Using Eqs. 3–5 the shape factor can be obtained

$$\varphi = (1-\varepsilon)^{-1} \left(2 \frac{\Delta p d_p \varepsilon^3}{\lambda_f \rho_g w^2 H_0} \right)^{1/(3-n)}. \tag{6}$$

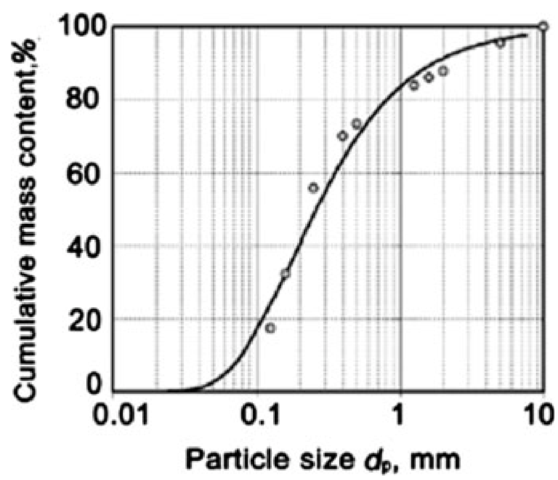

Figure 2. Cumulative particle-size distributions of ash samples from CFB boiler.

Table 1. Main Experimental Parameters

Parameter	Value
Height of unit, m	2.3
Column diameter, m	0.15
Exit from column to cyclone diameter, m	0.1
Porosity of distributor	0.017
Fluidizing air temperature, K	333
Fluidization pressure, hPa	1026–1060
Particle density, kg/m^3	2460
Gas velocity range, m/s	1.36-:-2.4
Particles size range, mm	1.02-:-1.25,mean 1.13
	1.25-:-1.6, mean 1.41
	1.6-:-2.0, mean 1.79
	2.0-:-5.0, mean 3.5
	5.0-:-10, mean 6.5

Because the Ergun equation (Eq. 5) has the best accuracy for spherical particles, then the shape factor φ for nonspherical particles could not be calculated directly from Eq. 6. An iterative procedure had to be applied then, in which the first proximate value of φ was obtained with an assumption $d_s = d_p$ in the definition of the Reynolds number. The diameter of the spherical particles was obtained then from a relation $d_s = d_p\varphi^{-0.5}$. After several iterations the value of the shape factor φ was stabilized. A simpler method[13] cannot be applied because the φ values were not coherent with the experimental attrition rates.

The attrition tests for the size groups given in Table 1 were conducted in a reactor made of steel (Figure 1). The initial mass of the ash samples $m(0) \in (0.6\text{-:-}0.85)$ kg was applied. Tests were stopped at regular time intervals and after particles removal from the bed their mass and size distribution was measured. The fines elutriated from the bed were captured in the cyclone, and in the filter bag, thus, then the mass balance has been controlled producing an average error of about 1%, with the maximum value below 5%. The superficial fluidization velocity was stabilized on a proper level monitored by pressure drop in the bed and controlled by fan.

Results and discussion

Figure 3 presents values of the shape factor evaluated for five particles size groups, where the particle size within the group is a geometrical mean of the lower and upper sieve size limits. Shape factors increases with particle size, which can be described by a correlation $\varphi = 1 + k_1 d_p^{0.5}$ with $k_1 = 30$ m$^{-0.5}$.

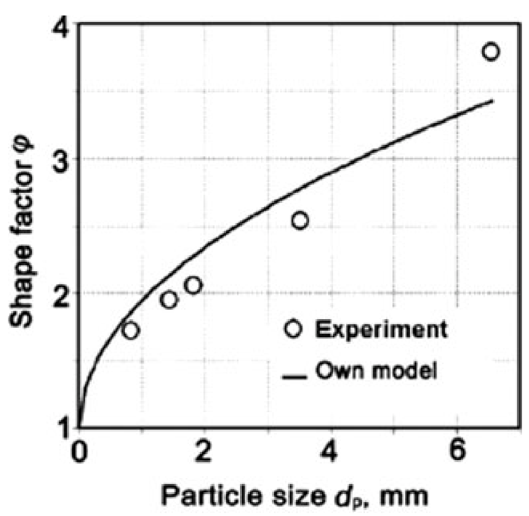

Figure 3. Shape factors vs. mean-particle size.

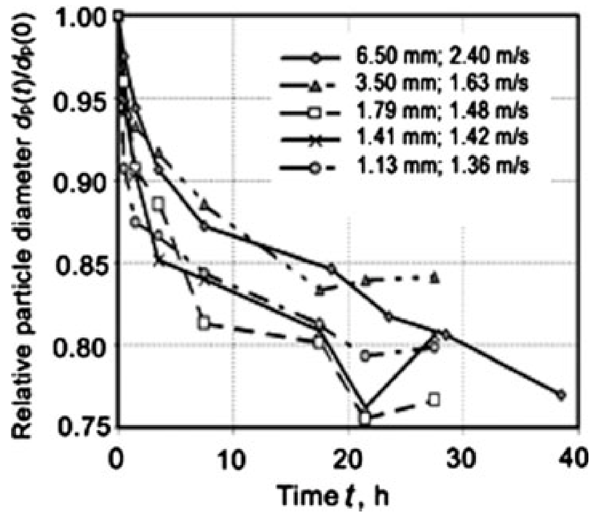

Figure 4. Relative mean bed-particles size vs. time for attrition of five groups of ash particles.

The results of attrition tests are presented in Figures 4, 5 and 6. Four size group experiments were conducted during 27.5 h, and for the fifth group, 38 h. The rate of attrition does decrease with time, but even after 38 h the remaining bed mass does not stabilize, as suggested by Lee et al.[4] and Cook et al.[5] The attrition models discussed in the state of art were tested on the basis of experimental data $m(t)/m(0)$, as presented in Figures 5 and 6. Examples of the modeling results by Cook et al.,[5] and by Highley and Merrick[2] models are presented in Figure 7, on a background of the experiments for one ash size group (1.79 mm). In the Cook et al. model the value of m_{min} has to be assumed arbitrary. It can be noticed that within the tested range $m_{\min}/m(0) = 0.75$-:-

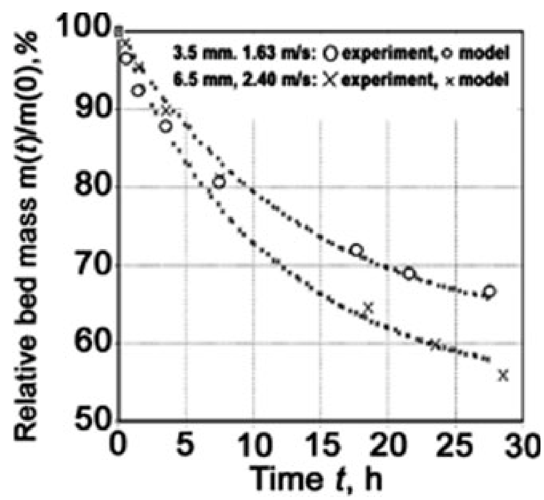

Figure 5. Comparison of the modeled and experimental relative bed mass remaining vs. time for attrition of two ash particles groups.

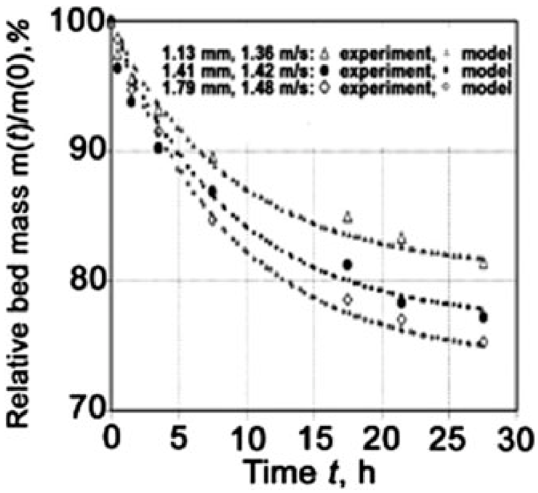

Figure 6. Comparison of the modeled and experimental relative bed mass remaining vs. time for attrition of three ash particles groups.

0.86 the three curves (1, 2 and 3) do not reproduce the experiments. What is more, the experimental attrition rate for long time does not tend to zero, as demand by Cook et al. model. The Highley and Merrick model also is not able to describe the experimental m(t)/m(0) curve, because the bed mass drops quickly to very low values. Even if for the Highley and Merrick model the attrition coefficient was modified it would be not able to get a proper curvature of the calculated m(t)/m(0) function. Figure 7 present clearly the weak points of the discussed models. For the other size groups the predictions from existing models are also far off, and for that reason are not presented. All the known models were able to describe the results only in a short time range. What is more, it was not possible to identify a minimum bed mass $m_{\min}$. Lee et al.[4] and Cook et al.[5] did not formulate any criteria for $m_{\min}$, and assumed this value arbitrarily, thus, this concept had to be abandoned. It was then necessary to develop a new model describing the experimental evidence:

- the largest rate of attrition is observed for high values of the bed mass, and for particles of large shape factor,
- the particles become smaller and more spherical with time as a result of attrition,
- attrition of particles is caused not only by mutual collisions, but also by collisions with the reactor walls.

In contrary to the published results, own experiments were conducted with various particle sizes and initial bed mass. This fact created problems with determination of the attrition rate controlling parameters. The broad particle-size range applied during the experiments made it clear that new variables must be included into the model to describe the observed results. The relation between the attrition rate and the bed mass, which is commonly used in all models was particularly difficult to correlate. Also, in order to include the contribution of the effect of particles collision with the reactor side walls to the attrition mechanism a ratio of the side wall surface area to the cross-section area, expressed by the ratio of the bed height H to the effective column diameter d_h, was proposed for consideration. Because the bottom part of the bed is filled by jets of mean height H_j, then an effective bed height $H_e = H - H_j$, correlated better the results then the H value. The jets height H_j was calculated by the equation given in.[14] Finally, the attrition model should include the following parameters: φ, H_e, d_h, w and w_{mf}. The best correlation has been obtained by the following equation

$$\frac{dm}{dt} = -k_a f(\varphi)\left(\frac{H_e}{d_h}\right)(w - w_{mf})m, \tag{7}$$

where the function $f(\varphi)$ was found by sensitivity analysis, based on the experimental $m(t)$ curves

$$f(\varphi) = \varphi^{-2}\exp\left[\frac{(\varphi^{0.75}-1)^{1.75}}{\varphi^2}\right]. \tag{8}$$

The form of the function $f(\varphi)$ is crucial for successful modeling and for spherical particles $\varphi = 1$, it should be equal $f(\varphi = 1) = 1$. Thus, the k_a coefficient expressed in m^{-1} presents a material property, which should be equal for all particle sizes. Because the chemical analysis of ash particles represents average composition of the ash sample, then certainly for each of the considered five size groups there were some deviations from the average. Nevertheless, it was possible to find the k_a value common for all particle-size groups within an error limit $\pm 27\%$.

The modeling procedure requires the knowledge of the particles diameter, and their shape factor as a function of time. Because the fines produced during attrition are immediately elutriated, then it was possible to assume a constant number of particles in the bed. Applying a numerical proce-

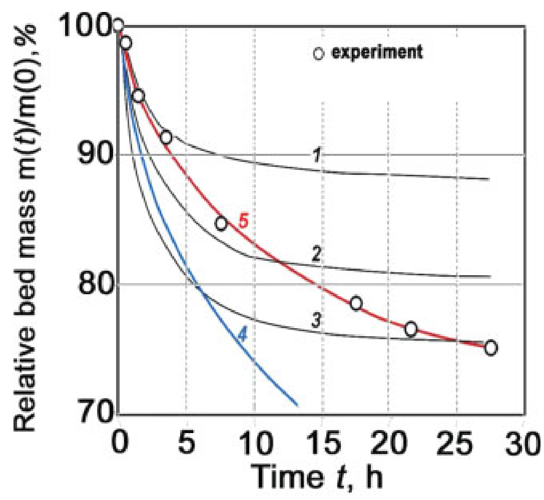

Figure 7. Relative-bed mass remaining vs. time for attrition of one size group 1.79 mm, w = 1.48 m/s: (1) Cook et al. model for $m_{\min}/m(0)$ = 0.86, (2) Cook et al. model for $m_{\min}/m(0)$ = 0.80, (3) Cook et al. model for $m_{\min}/m(0)$ = 0.75, (4) Highley and Merrick model, and (5) own model.

Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.

dure with a time interval of 30 s, it was possible to describe the experimental curves $m(t)/m(0)$ for all size groups, as presented in Figure 5 and 6. A very important modeling parameter, the coefficient of attrition has been found $k_a = (1.5 \pm 0.4) \cdot 10^{-4}\ m^{-1}$, which value is almost constant for all five size groups, and can be considered then as a material property for the examined ash particles.

It should be noticed that the previously published models also relate indirectly the rate of attrition to the geometry of the fluidized bed, because the particles mass in the bed is proportional to the bed volume. For example, in the Highley and Merrick model[2] the attrition rate depends then on a function Hd_h^2, while for the proposed model the attrition rate is proportional to the function $H^2 d_h$.

Conclusion

During the process of mechanical attrition in fluidized beds the shape of ash particles alters much with time as a consequence of sharp edges abrasion.

The bed mass does not stabilize during long fluidization time of ash particles even after 38 h experiments, thus, the assumption of a minimum bed mass during attrition process is not justified.

The proposed model of particles mechanical attrition in fluidized beds describes well the mass loss in long experimental time. The variation of the particle shape factor is essential for successful attrition modeling.

Further research of solid particles attrition in fluidized beds are required for reactors of different diameters in order to separate the mechanism of attrition caused by mutual particle-particle collisions from that by reactor walls — particle collisions.

Notation

d_h = effective bed diameter, m
d_s = spherical particles diameter, m
d_p = mean-particle sieve size, m
H = bed height, m
H_0 = stagnant bed height, m
H_e = effective bed height, m
K_a = particle-attrition coefficient, s^{-1}
k_a = particle-attrition coefficient, m^{-1}
m = mass of bed particles, kg
m_{min} = minimum mass at which attrition is negligible
w = superficial gas-fluidization velocity, ms^{-1}
w_{mf} = minimum superficial-gas-fluidization velocity, $m \cdot s^{-1}$
Re = $wd_s v_g{}^{-1}$ Reynolds number
t = time, s
λ_f = friction factor
ε = mean-bed voidage
v_g = kinematic gas-viscosity coefficient, $m^2 s^{-1}$
φ = particles shape factor
ρ_g = density of fluidizing gas, kgm^{-3}
ρ_p = particles density, kgm^{-3}

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