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FLUIDIZED BED COMBUSTION OF HIGH ASH ANTHRACITE: ANALYSIS OF COMBUSTION EFFICIENCY AND PARTICLE SIZE DISTRIBUTION

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Abstract—Fluidized bed combustion of high ash anthracite (HAA) was experimentally studied. The combustor consists of 0.25 m ID bed, and auxiliary equipments for coal feeding, ash removal, temperature control, etc. Experimental results elucidate main cause of fuel loss to be elutriation of fines (i.e., flyash) containing unburned carbon. However, detailed balances of particle size distribution show majority of carbon in flyash comes from fines contained in the feed instead of attrition of coarse particles. The latter is the main source of flyash for conventional coal. The difference is due to much smaller attrition rate of HAA; feed HAA particles do not shrink much in size by combustion and attrition.

INTRODUCTION

High ash anthracite(HAA), which contains more than 60% of ash by weight, has low calorific value(less than 13,000 kJ/kg) and poor combustion characteristics. On the other hand it represents roughly 40% of coal reserve in Korea where coal is the only sizable fossil energy resources. Thus as an endeaver to exploit domestic energy resources fluidized bed combustion (FBC) of HAA has been tested on pilot plant scale[1].

Owing to excellent contact of fuel with air and large heat reservoir FBC has been proved as a powerful tool for the combustion and utilization of difficult-to-burn-fuels as well as conventional coal. FBC technology for conventional coal has reached commercialization stage already[2]. However, some problem areas still remain with HAA, and one of the most important of them is low combustion efficiency. Because of high ash content a significant fraction of already low heating value is lost with ash particles removed from the combustor. This makes attaining high combustion efficiency more important with HAA than with conventional coals. In order to analyze combustion efficiency one needs to investigate on the loss of fuel from the combustion system.

There are three forms of fuel loss in FBC: (1) CO and other combustible gases in flue gas. (2) Unburned fuel contained in flyash which are small particles entrained with combustion gas out of the combustor. (3) Unburned fuel contained in "overflow" solids which are withdrawn from the bed to maintain stable bed depth. It is generally known that fuel loss with flyash is the most important.

In FBC relatively large coal particles can be fed to the combustor thus saving costs associated with crushing and grinding. Ideally feed coal does not need to have small particles which can be easily entrained out of the bed before complete combustion. However, some fine particles are inevitably generated during crushing of coal. Fines can be produced in the coal feed line where coal particles rub each other or with the inner surface of conveying line. Inside a fluidized bed coal particles can break into several smaller particles owing to thermal shock as they experience a very rapid temperature rise. But even more fines can be generated by attrition in the bed. Massimilla and his coworkers published a series of papers to elucidate the importance of attrition [3-7].

But their experiments are limited to low ash coal particles which allow neglect of ash. But in the case of HAA ash does not peel off, and shrinking particle model does not hold: HAA particles retain their size and shape through combustion. In this paper we present experimental results of FBC of HAA together with the analysis on the effect of attrition.

EXPERIMENTAL

A schematic diagram of the fluidized bed combustion used in this study is shown in Figure 1. The inside diameter of the combustor is 0.25 meter and its height from the distributor plate is 4m. Inside diameter of upper one meter of the combustor is expanded to 0.394 meter to reduce gas velocity, thereby entrainment of

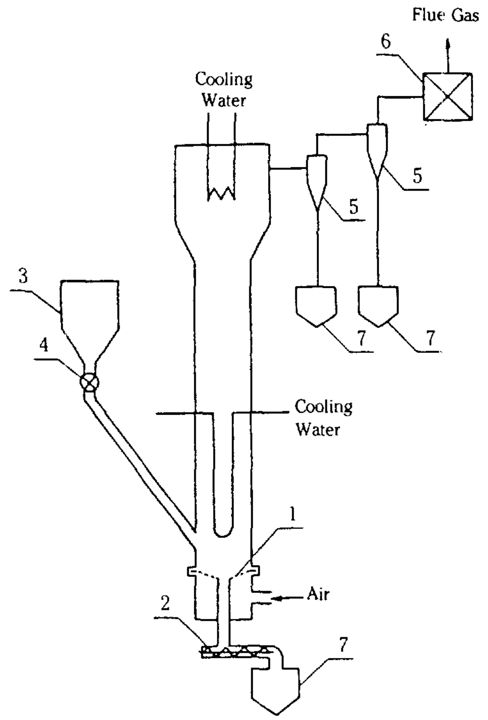

Fig. 1. Schematic diagram of experimental set-up.
1. distributor plate, 2. screw feeder for bottom ash removal, 3. coal hopper, 4. rotary valve, 5. cyclone, 6. bag filter, 7. hopper

fines (small particles).

Continuous coal feeding is rendered by a pre-calibrated rotary valve and opening of feed line lies 0.2m above the perforated type distributor plate. Excess bed particles are withdrawn continuously from the bottom of the bed through a hole centered in the distributor. By adjusting rotating speed of screw feeder constant bed height can be maintained. Bottom ash line is water-cooled. A Roots type blower supplies fluidizing air. An oil burner is used for start-up of the combustor. Cooling tubes are installed in the bed for temperature control. Pressure taps and thermocouples are installed at various locations. Two stages of cyclone and a bag filter removes flyash entrained by combustion gas which passes through an induction draft fan before discharge into the atmosphere.

For each run of experiment, samples of solid particles are taken at steady state for a period of 30 minutes in each "stream", bottom ash, first cyclone catch, second cyclone catch, and bag filter catch. Notice that flyash is the summation of the latter three. Knowing feed rate we can measure combustion efficiency from the quantity and composition of bottom ash and flyash assuming no solid particles are lost to the atmosphere. Furthermore we can set up mass balance for each size interval by sieving and proximate analysis of feed, bottom ash, and flyash. In this way we can follow changes in size distribution of feed coal through combustion and attrition.

Table 1. Analysis of high ash anthracite

Ultimate	wt %	Proximate	wt %
C	31.93	Moisture	1.97
H	0.13	Volatile	2.34
O	0.70	Fixed Carbon	28.29
N	4.13	Ash	67.40

High ash anthracite, produced in Bosung, Choongnam is used for the experiment. Composition of HAA can vary significantly from particle to particle. A representative value for its analysis is summarized in Table 1. Feed is crushed so that about 98% of it passes through No 8 mesh screen. Notice that HAA retain their sizes through combustion thus obviating the addition of separate bed material (e.g. sand) to the bed. Therefore the bed consists mostly of HAA ashes.

RESULTS AND DISCUSSION

1. Combustion Efficiency

Experimental runs were made under various conditions to investigate effects of bed temperature, bed depth and fluidizing gas velocity on combustion efficiency. In this study we defined combustion efficiency as follows:

1-(fixed carbon in effluent streams)/(fixed carbon in the feed).

Table 2. Combustion efficiency under various conditions

Run No.	Bed Temperature (°C)	Bed Height (m)	Fluidizing Gas Velocity (m/s)	Combustion Efficiency (%)	Excess Air (%)
1	800	0.35	0.9	78.8	10
2	800	0.35	1.8	52.5	20
3	800	0.55	0.9	66.5	20
4	800	0.55	1.8	60.2	20
5	800	0.75	0.9	71.6	20
6	800	0.75	1.2	66.8	20
7	800	0.75	1.8	58.8	20
8	900	0.35	0.9	76.3	20
9	900	0.35	1.8	66.1	20
10	900	0.75	1.8	73.9	20

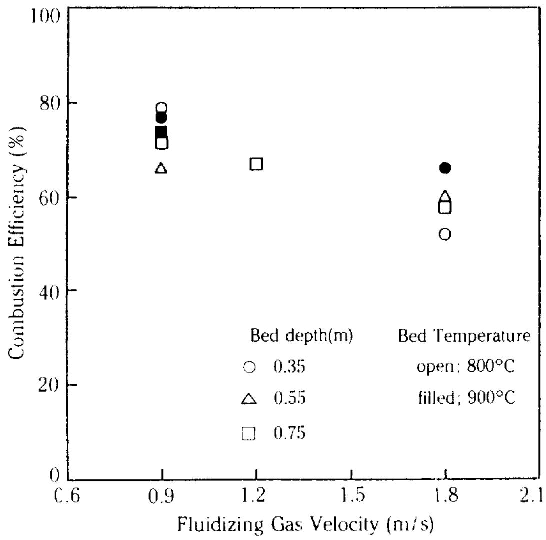

Fig. 2. Effect of fluidizing gas velocity on combustion efficiency.

Operating conditions and resulting combustion efficiency for each run are listed in Table 2, and plotted in Figure 2 as well. As we can notice in Figure 2 combustion efficiency increases with bed temperature and bed depth. We can also notice that combustion efficiency decreases markedly with increase of fluidizing gas velocity.

Close look at combustion efficiencies reveals that most of fuel loss is indeed associated with unburned carbon in flyash: Table 3 shows 84 to 95% fuel loss is from flyash. Concentration of CO in flue gas is negligibly small and its contribution to fuel loss is less than one percent of fuel input. Therefore investigation is required to elucidate the source of those carbon containing fines(flyash) which are elutriated from the combustor.

2. Particle Size Distribution and Fixed Carbon Content of Feed, Flyash and Bottom Ash

Particle size distribution of feed, flyash and bottom ash for Run 8 and Run 9 obtained from sieve test are plotted in Figure 3. With the same size distribution for feed particles higher fluidizing gas velocity results in

Table 3. Fuel loss analysis by stream

(wt %)

Stream	Run No 8	Run No 9
Flyash	21.2	34.1
Bottom Ash	4.2	1.9
Total	25.4	36.0
Combustion Efficiency	74.6	64.0

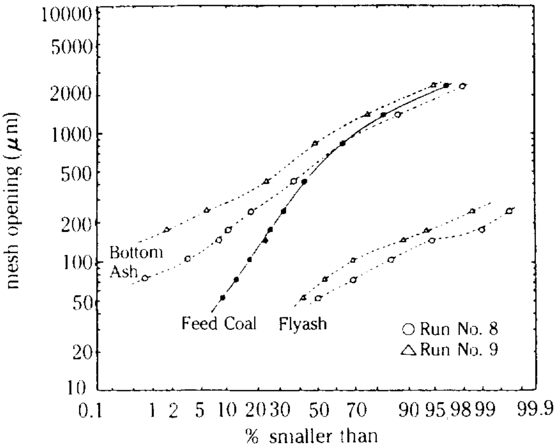

Fig. 3. Particle size distribution of feed, flyash and bottom ash.

larger particles for both bottom ash and flyash. This is consistent with the general concept in elutriation. Not only small particles, which can be elutriated readily at modest gas velocity, but relatively large particles can be elutriated at increased gas velocity. At the same time, relatively a large fraction of feed elutriates. But the bottom ash, deprived of more fines, also has larger average particle size.

HAA contains very little votatiles. Thus accounting of fixed carbon only is termed as carbon balance in this study. The entire range of feed size distribution is divided into ten size intervals and proximate analysis is made for the measurement of fixed carbon content in each size interval and stream. As we can see in Figure 4 fixed carbon content varies with particle size. Notice that abscissa of Figure 4 and followings is not in scale but represents sieve size of size intervals, and these histrograms are adopted for convenience in pre-

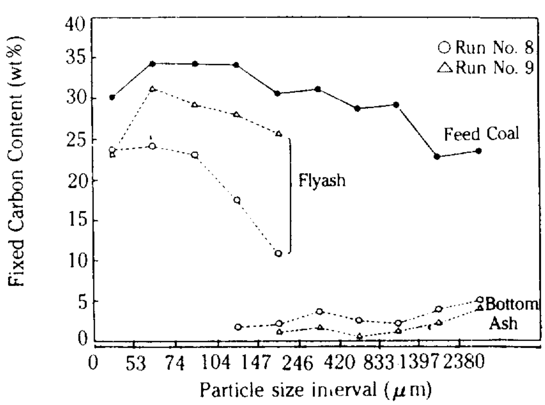

Fig. 4. Fixed carbon content in each size interval of feed, flyash and bottom ash.

senting data from sieve test. With the exception of the smallest size (smaller than 53 μm) fixed carbon increases with decrease of particle size. Visual observation shows large feed particles are very heterogeneous in color and shape: fixed carbon content can vary widely from particle to particle of similar size. For flyash fixed carbon content varies even more with particle size. Flyash from higher fluidizing gas velocity contains higher fixed carbon content (Run 9 over Run 8). However, bottom ash does not reveals such a trend. Fixed carbon content of largest particles (>2380 μm) is above average. Moreover, bottom ash at higher fluidizing gas velocity contains less fixed carbon. This is contradictory to the fact that residence time of HAA decreases with increase of gas velocity (with values for other parameters unchanged).

3. Material Balance for Each Size Interval

For each size interval we have the following material bal. ıce:

$$F_i - O_i = C_i + A_i + S_i - S_{i+1} \quad \text{for} \quad i = 2, 3 \cdots, N-1 \tag{1}$$

Where F_i = feed rate of particles in i-th size interval (kg/hr)

O_i = exit rate of particles in i-th size interval from the combustor (kg/hr)

C_i = loss of mass due to combustion in i-th size interval (kg/hr)

S_i = loss rate of mass in i-th size interval to i-1th size interval by size reduction due to attrition (kg/hr)

A_i = loss of mass due to attrition in i-th size interval (kg/hr)

N = total number of size intervals

Notice that exit rate, O_i, consists of flyash and bottom ash removal rate. S_i represents change in size interval due to attrition[8]. Here we assumed that size of fines generated by attrition is very small compared to mother particles and all of them falls into smallest size interal. For the smallest and the largest size intervals we have

$$F_1 - O_1 = C_1 - A - S_2 \tag{2}$$

$$F_N - O_N = C_N + A_N + S_N \tag{3}$$

when $A = \sum_{i=2}^{n} A_i$ is the total production rate of fines by attrition in the bed. Then total combustion rate of carbon in the bed, C, can be given as

$$C = \sum_{i=1}^{n} C_i = F - O \tag{4}$$

where

$$F = \sum_{i=1}^{n} F_i$$

$$O = \sum_{i=1}^{n} O_i$$

Figure 5a and 5b show F_i and O_i for i = 1 to 10. Notice that i = 1 corresponds to the smallest size interval (<53 μm) and i = 10 to the largest (>2380 μm). We can observe that F_i is larger than O_i for i = 4 to 10 but the opposite is true for i = 1 to 3. In order to elucidate the effect of attrition we can exclude mass loss from combustion by taking only ashes. The results as shown in Figure 6a and 6b show distrinctive shift in size distribution. Exit streams (flyash combined with bottom ash) contain less large particles, but much more small particles compared to the feed. We can also observe that most of small particles leave the bed as flyash while most of large particles do as bottom ash. We notice that O_i is larger than F_i for i = 1 to 5 while the reverse holds for i = 6 to 10. For i = 1 this is as expected from Equation(2) when $C_i = 0$. Even though we do not know values of S, we can explain differences between O_i and F_i for i = 2 to 10. If $S_i = S_{i+1}$ and $A_i > 0$, then $F_i > O_i$ as $A_i > 0$ in Equation(1). This could explain Figure 6a and 6b for i = 6 to 10. But for i = 2 to 5 it is possible to have $A_i < S_{i+1} - S_i$ because

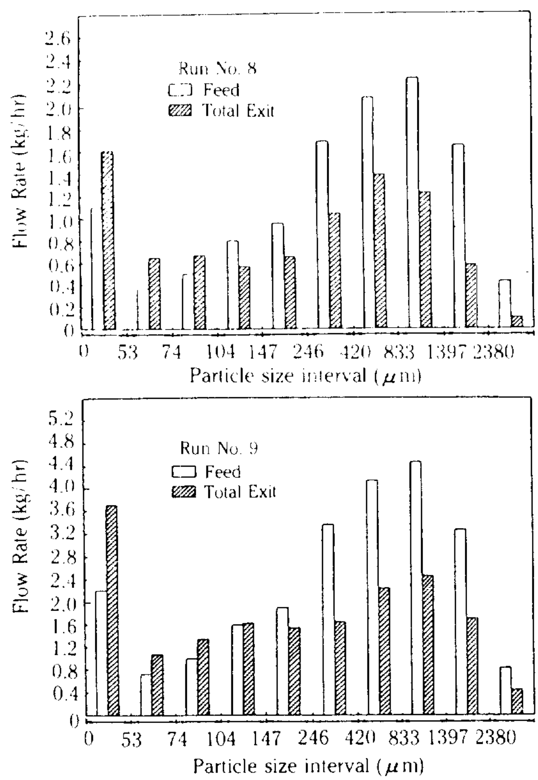

Fig. 5. Total solids balance for all size intervals (a for Run 8 and b for Run 9).

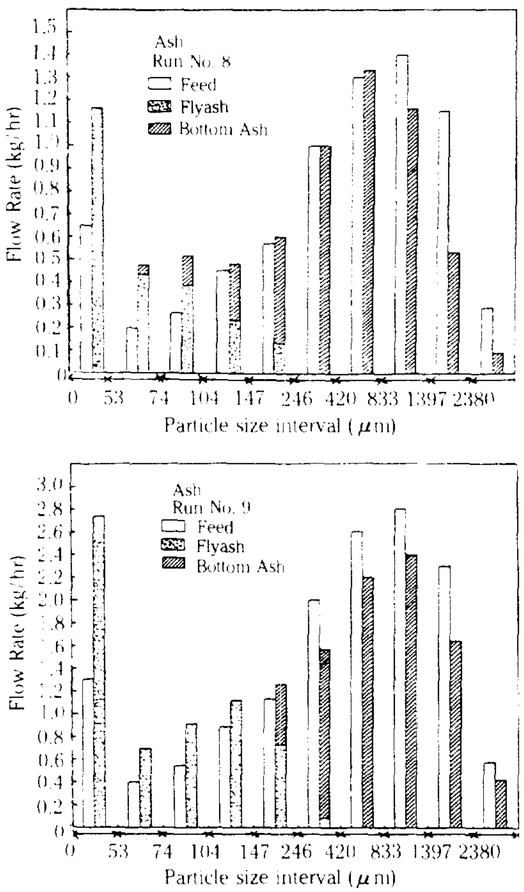

Fig. 6. Ash balance for all size intervals (a for Run 8 and b for Run 9).

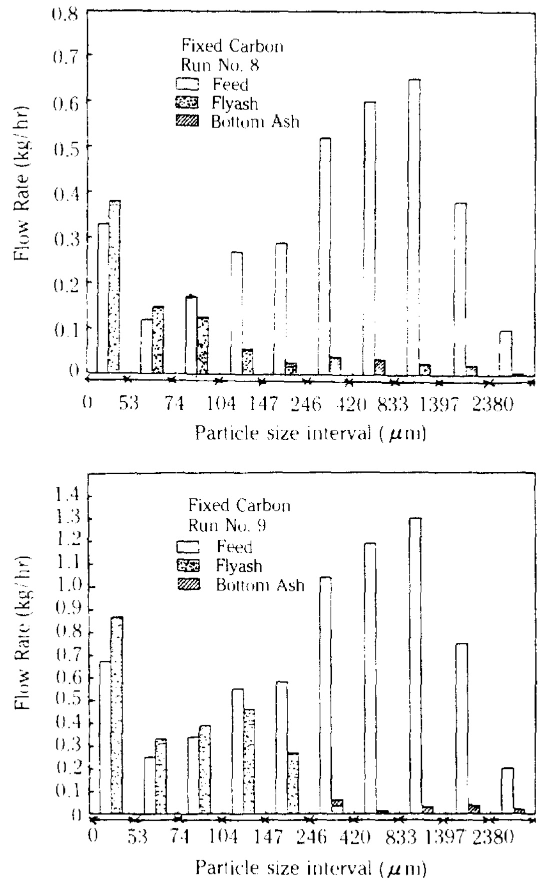

Fig. 7. Fixed carbon balance for all size intervals (a for Run 8 and b for Run 9).

$F_{i+1} > F_i$ and S_i could be proportional to F_i. Moreover, some of attrition products can be larger than 53 μm. Arena et al.[9] reported size range of attrition products from a few microns to 240 μm. This size range coincidentally covers i = 1 to 5 of this study.

When we take only fixed carbon for mass balance in each size interval the result shows that most unburned fixed carbon leaves the bed as flyash (Figure 7a and 7b). This is consistent with the result of Table 3.

Small particles, whose terminal velocity is smaller than prevailing superficial gas velocity in the freeboard region of the bed, are readily entrained out of the bed. Fines in the feed as well as those generated by attrition thus have very short residence time to be burned to a significant degree.

4. Attrition Rate in the Bed

Attrition of coal particles occurs in various places of the bed by various mechanisms such as rubbing each other, impingement on the bed wall and the distributor plate, jetting gases from the distributor plate, etc. There could be some attrition or fracture of particles in the feed line, bottom ash removal line, and cyclones. However, attrition in the feed line of this study is considered to be small because feed particles pass through a slowly rotating rotary valve and then slide down by gravity to the bed. There can be some attrition in bottom ash removal line as bottom ash passes through a screwfeeder and residence time in the removal line is rather long. Size distribution of bottom ash shows that it has very small amount of fines, thus attrition in the bottom ash removal line does not incur any significant error in the balance of fines in the bed. Flyash also can go through size reduction owing to high velocity actions involved around cyclones. Nevertheless flyash particles are of small size which are elutriated already. Thus neglecting futher attrition in the cyclones we can now estimate the generation rate of fines by attrition from mass balance for small particle size intervals. For this we employ total solids balance, instead of ash or fixed carbon. We take those fines that have output

Table 4. Attrition rate and attrition rate coefficient

	Run 8	Run 9
A′(kg/sec)	1.53×10^{-5}	3.53×10^{-5}
U_o (m/s)	0.9	1.8
[1] U_{mf}(m/s)	0.15	0.2
[2] W_{Bed} (kg)	17.7	17.7
[3] $\bar{d}$ (m)	6×10^{-4}	8.5×10^{-4}
k.	1.2×10^{-8}	1.88×10^{-8}

1. estimated.
2. estimated from data for pressure profile(vertical) in the bed.
3. 50% cut by weight from sieve test of bed material sample.

larger than input ($O_i > F_i$) as the ones which can be produced by attrition. Then we can obtain total production rate of fines by summation of output minus input for each size interval:

$$\text{Attrition Rate} = \sum_i O_i - F_i \text{ for all i, provided } O_i > F_i$$

Then attrition rate coefficient [9],

$$K = \frac{A'}{(U_o - U_{mf})\,w/\bar{d}}$$

can be estimated. The result is summarized in Table 4. Compared to values reported by Massimilla[7](0.72×10^{-7}–7.01×10^{-7}) attrition rate coefficient of HAA in this study is very small even without considering possible attrition in cyclones. Furthermore we can see from Figure 7a and 7b that attrition does not add much to fixed carbon loss by flyash. Fines in the feed is the main source of unburned fines. Therefore to increase combustion efficiency we need to have feed which does not have much fines. If that is not possible we should separate feed coal into fine and coarse particles, and burn them in separate combustors operating under different conditions for the overall optimization of combustion efficiency.

CONCLUSIONS

Fluidized bed combustion of high ash anthracite (HAA) was experimentally studied using a 0.25 m ID bed. Experimental results show combustion efficiency is higher with higher bed temperature and lower fluidizing velocity. However, combustion efficiency of HAA is much smaller than that of ordinary coals.

Particle size distribution of feed, flyash and bottom ash together with analysis of fixed carbon content for each size interval and stream elucidate main cause of fuel loss to be elutriation of fines containing unburned carbon. But unlike ordinary coals, for which attrition can produce a significant amount of fines in the bed, majority of carbon in HAA flyash is from the feed. Attrition rate coefficient of HAA is found to be much smaller than that of other coals. Therefore in order to increase combustion efficiency of HAA in FBC a separate combustion of fine and coarse particles is necessary: after separating fines from raw HAA coarse particles can be burned at relatively high fluidizing gas velocity while fines are burned in a separate bed operating at much lower fluidizing gas velocity thus ensuring sufficient combustion in the bed. More stuides are needed for the better combustion of HAA fines.

NOMENCLATURE

- $\bar{d}$: mean particle size in the bed (m)
- A_i : loss of mass due to attrition in i-th size interval (kg/hr)
- A : production rate of fines by attrition in the bed (kg/hr)
- A′ : production rate of fines by attrition in the bed (kg/sec)
- C_i : loss of mass due to combustion in i-th size interval (kg/hr)
- C : total combustion rate of carbon in the bed (kg/hr)
- F_i : feed rate of particles in i-th size interval (kg/hr)
- F : total feed rate of solids into the bed (kg/hr)
- O_i : exit rate of particles in i-th size interval from the combustion (kg/hr)
- O : total exit rate of solids from the bed (kg/hr)
- S_i : loss rate of mass in i-th size interval to i-1th size interval by size reduction (kg/hr)
- U_o : superficial fluidizing gas velocity through the bed (m/s)
- U_{mf} : superficial gas velocity at incipient fluidization (m/s)
- W : weight of bed (kg)

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