The Behavior of Fine Particles in the Powder Particle Fluidized Bed

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Abstract

The powder particle fluidized bed was invented for the processing of fine or very fine particles. In a powder particle fluidized bed, fine powders are continuously fed to a bed in which coarse particles have been fluidized. The fine powders are uniformly dispersed and fluidized in the bed, where they adhere to the surface of the coarse particles. Fine particles are then elutriated from the bed with gas.

This study entailed the use of a powder particle fluidized bed to investigate the holdup of fine particles in the bed, the elutriation rate constant of fine particles from the bed, and the average residence time of fine particles in the bed.

The holdup of fine particles increased linearly with an increase in the feed rate of fine particles and the holdup of fine particles increased with decrease in gas velocity and the particle size of fine particles.

The elutriation rate constant of fine particles increased when fine particle size and gas velocity increased, and decreased when coarse particle size increased. The average residence time of fine particles increased when gas velocity and fine particle size decreased. When fine particle size was smaller than several microns, the average residence time of fine particles in the bed was more than 1,000 times as long as that of the fluidized gas.

Introduction

Fluidized beds are used in gas-solid catalytic reactors, in gas-solid reactors, and for physical operations such as particle drying or granulation.

Fig. 1 shows Geldart's classification of fluidization patterns. Fig. 2 shows the classification of fluidized beds. "A" particles are used in fluid beds, which are used as gas-solid catalytic reactors. "B" particles are used in teeter beds, which are employed as gas-solid reactors or for physical operations. "D" particles are used in spouted beds. However, "C" particles are usually not used in fluidized beds owing to the following two disadvantageous characteristics for fluidization. First, C particles are quite difficult to fluidize and in some cases they are fluidized by self-agglomeration. Second, because the terminal velocity of C particles is slower than 5 cm/s, if the superficial gas velocity in the bed is very high, all the particles in the bed are carried out with gas. But C particles have many attractive properties. If they are dispersed in the bed uniformly, the reaction between gas and particles is very fast. For example, if 100 µm particles complete the reaction in 100 s, 10 µm or 1 µm particles can complete the reaction in about 10 s or 1 s, respectively. If C particles are dispersed in the bed uni-

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formly, the specific surface area of the particles is quite large and the heat or mass transfer rate between gas and particles is very fast.

Recently we invented a new type of fluidized bed, called a powder particle fluidized bed, for the processing of C particles. A diagram of the apparatus appears in Fig. 3. C particles are continuously fed to the bed in which coarse B or D particles have been fluidized. C particles are uniformly dispersed and fluidized in the bed, where they adhere to the surfaces of the coarse particles. The fine particles are elutriated from the bed with gas. A powder particle fluidized bed is used for the production of porous fine particles [1,2] and very fast reactions between particles and gas [3,4] and the reaction between fine particles, coarse particles and gas [5,6] and drying of slurry [7,8].

To analyze the reaction performance or physical operation in a powder particle fluidized bed, it is very important to investigate the behavior of fine particles in the bed.

This study used a powder particle fluidized bed to investigate the holdup of fine particles in the bed, the elutriation rate constant of fine particles from the bed, and the average residence time of fine particles in the bed.

**Experimental apparatus and experimental method**

Fig. 4 shows the experimental apparatus. The column used in this experiment was a vinyl chloride column with a 10 cm inside diameter and a height of 70 cm. Coarse particles several hundred μm in size were fed into the column until the static bed height became 10 to 30 cm and the particles were fluidized with air.

Fine particles were continuously fed into the bed and fluidized with coarse particles, then elutriated from the bed. The elutriation rate of fine particles from the bed was measured by weighing the bag filter at certain time intervals. Once the elutriation rate of fine particles became constant, the system was considered to have achieved a steady state. At this point the feeds of both air and fine particles were immediately stopped, and the mixture of fine and coarse particles in the bed was removed to measure the content of fine particles, which was determined by separating the fine particles from the mixture in water.

Most of the fine particles in the bed had adhered to the surfaces of coarse particles. But some fine particles in the bed had agglomerated into secondary particles with sizes of 50-200 μm. The amount of these agglomerated particles was determined by the following procedure. The small amount of bed particles was screened with a sieve that had a smaller mesh size than the size of the coarse particles. Most of the agglomerated particles were screened out. Their weight was obtained by weighing the sample before and after screening. The holdup of fine particles \( X \) was calculated from Eq. (1) by measuring the total weight of fine particles \( W_p \) and total weight of coarse particles \( W_{cp} \) in the bed.

\[
X = \frac{W_p}{W_{cp}} \quad (1)
\]

The elutriation rate constant was calculated with the following equation.

\[
R = KAX \quad (2)
\]

If the holdup of fine particles \( X \) and the elutriation rate of fine particles \( R \) are measured in the steady
state, the elutriation rate constant $K$ is calculated from Eq. (2).

The average residence time of fine particles in the bed was obtained as follows.

$$\bar{\theta}_p = \frac{W_p}{R}$$

(3)

Table 1 shows the properties of the fine and coarse particles used in this experiment.

### Table 1 Physical properties of particles

| Particles               | $d_p$ [µm] | $\rho_p$ [kg/m³] | $U_{in}$ [m/s] |
|-------------------------|------------|------------------|----------------|
| Silica sand             | 460        | 2.650            | 0.17           |
|                         | 550        | 0.26             |
|                         | 780        | 0.38             |
|                         | 920        | 0.51             |
| Activated alumina       | 550        | 1.350            | 0.13           |
|                         | 780        | 0.23             |
| Glass beads             | 550        | 2.600            | 0.24           |
| Al(OH)$_3$              | 15         | 2.400            |                |
|                         | 3          | 2.400            |                |
| Al$_2$O$_3$             | 3          | 4.000            |                |
|                         | 1.3        | 4.000            |                |
| CaCO$_3$                | 10         | 2.710            |                |

1. **Holdup of fine particles in a powder particle fluidized bed (PPFB)** [9]

The holdup of fine particles in a PPFB is determined by the balance between the rate by which fine particles adhere to the surface of coarse particles, and the rate by which fine particles separate from coarse particles due to coarse particle collisions. The holdup of fine particles in the bed is affected by the feed rate of fine particles, the size and density of fine and coarse particles, and the superficial gas velocity.

**Fig. 5** shows the effect of superficial gas velocity on the holdup of fine particles. When gas velocity increased, coarse particle fluidization became violent, with frequent collisions of coarse particles and decreasing holdup of fine particles. **Fig. 6** shows the relationship between the fine particle feed rate and fine particle holdup, with coarse particle size as a parameter. Fine particle holdup increased linearly as the feed rate increased. When coarse particle size was small and gas velocity was constant, the holdup of fine particles in the bed became small. $U-U_{in}$ values became large when coarse particles were small, and when their size decreased, the fluidization of coarse particles became more violent and the holdup of fine particles decreased. **Fig. 7** shows the effect of superficial gas velocity on the holdup of fine particles in the bed, with fine particle size as a parameter. This figure shows that when fine particle size decreased, their holdup in the bed increased remarkably. When fine particle size was small, the force by which fine particles adhered to coarse particles became large, and holdup increased greatly.

In a powder particle fluidized bed, fine particles are present in the bed in the following three situations.

1. Fine particles adhere to the surfaces of coarse particles.
2. Fine particles mutually agglomerate and form secondary particles with particle sizes of 50-200 µm.
3. Fine particles agglomerate with coarse...
and fine particles to form very large secondary particles with sizes of 600-10^4 μm. When the holdup of fines in the bed was small, most of them adhered to the surfaces of coarse particles, but when the holdup of fine particles increased, the fractions of types (2) and (3) increased and in some instances steady state operation became impossible. The state of fine particles (3 μm Al(OH)_3) in the bed was investigated when 550 μm silica sand particles were fluidized with air. Fig. 8 shows the relation between the total holdup of fine particles and the holdup in (1) (adhesion ratio). When the total holdup of fine particles was less than 3%, most of the holdup fine particles in the bed adhered to coarse particles, but when the holdup was larger than 3%, type (2) holdup increased as the total holdup of fine particles increased. When total holdup was larger than 8%, very large agglomerate particles formed in the bed and steady state operation became impossible. Therefore if fine particles are to come into contact with gas at the primary particle situation, the holdup of fine particles in the bed must be less than 3 or 4%.

2. Elutriation of fine particles from the powder particle fluidized bed [10]

When fine particles several μm in size were fed into a bed in which coarse particles have been fluidized, the fine particles were not elutriated from the bed at first. But the elutriation rate of fine particles increased as time passed, and it became constant after a certain period of time. When the fine particles were fed into a bed in which the coarse particles had been fluidized, the holdup of fine particles increased with the passage of time. When the separation rate of fine particles from coarse particles due to mutual collisions by coarse particles equalled the adhesion rate of fine particles to the surfaces of coarse particles, the elutriation rate of fine particles from the bed became constant. The rate constant K was calculated from Eq. (2) by measuring holdup X and the elutriation rate R.

Fig. 9 shows the relation between the superficial gas velocity and the elutriation rate constant, with coarse particle size as a parameter when 3 μm particles of Al(OH)_3 were fed into the bed. The rate constant increased as gas velocity increased. This tendency is the same as that of Geldart A and B particles. However, the elutriation rate constant of C particles was affected by the size of coarse particles, as shown in Fig. 9. This differs considerably from the elutriation rate of A or B particles. Much experimental or theoretical work has been performed on the elutria-

![Fig. 8](image1.png)  
**Fig. 8** Relationship between the holdup of fine particles and adhesion ratio.

![Fig. 9](image2.png)  
**Fig. 9** Effect of gas velocity and coarse particle size on the elutriation rate constant.
the C particle region the elutriation rate constant decreased as particle size decreased owing to the adhesion force of fine particles. When the holdup $X$ of fine particles in the bed was smaller than $8\%$, the elutriation rate constant was not affected by the holdup.

3. Average residence time of fine particles in the bed [12]

It is very important to investigate the average residence time of fine particles and the residence time distribution of fine particles in the bed in order to analyze the reaction between fine particles and gas or to analyze the drying of slurry in a powder particle fluidized bed. The average residence time of fine particles is calculated from Eq. (3) by measuring the elutriation rate of fine $R$ and the total holdup of fine particles in the bed in a steady state. The average gas residence time in the bed is calculated as follows.

$$\bar{\theta}_g = \frac{A L_{mf} (1 - \varepsilon_{mf})}{Q} = \frac{A L (1 - \varepsilon)}{Q}$$  \hspace{1cm} (4)

Where $Q$ is the volume flow rate of fluidized gas and $L_{mf}$ is the bed height at minimum fluidized gas velocity.

We investigated the effects of the properties of fine particles and the operating conditions upon $\bar{\theta}_g/\bar{\theta}_g$. Fig. 11 shows the relation between $\bar{\theta}_g/\bar{\theta}_g$ and the superficial gas velocity, with fine particle size as a parameter. When the gas velocity increased, the dimensionless average residence time of fine particles $\bar{\theta}_g/\bar{\theta}_g$ decreased because of the violent fluidization of coarse particles. The value of $\bar{\theta}_g/\bar{\theta}_g$ was strongly affected by fine particle size. The dimensionless average residence time of fine particles increased as the size of fine particles decreased. When fine particles were several $\mu$m in size, the value of the dimensionless average residence time of fine $\bar{\theta}_g/\bar{\theta}_g$ was longer than $1,000$ s. The dimensionless average residence time of fine particles was also affected by the size and density of coarse particles, and the humidity of the fluidizing gas.

From the foregoing we can see that the most important factor affecting the average residence time of fine particles in the bed was fine particle size.

When fine particle size was in the range of several to $20 \mu$m, the dimensionless average residence time of fine particles in the bed was in the range of $1,000$-$100$ s. In powder particle fluidized beds, fine particles less than $10 \mu$m remained in the bed more than several hundred times longer than the average gas residence time in the bed with primary particle situation between gas and particle contacting. In gas-solid reactions, the time necessary to complete the reaction is very short when the particles are very small.

Powder particle fluidized beds are very good reactors for reactions between gas and fine particles, and for performing physical operations on fine particles.

Conclusion

The authors used a powder particle fluidized bed to investigate the holdup of fine particles in the bed, the elutriation rate constant of fine particle from the bed, and the average residence time of fine particles. Following are the results.

(1) The holdup of fine particles was affected by the fine particle feed rate, the properties of fine and coarse particles, and gas velocity. The state of fine particles in the bed was affected by the value of holdup in the bed.

(2) The elutriation rate constant of fine particles increased with increases in gas velocity and in fine particle size, and decreased with an increase in coarse particle size. However, it was not affected by the holdup of fine particles.

(3) The average residence time of fine particles in the bed increased when gas velocity and fine particle
size decreased. When the size of fine particles was smaller than 10 μm, their average residence time in the bed was more than several hundred times longer than that of gas residence time.

**Nomenclature**

- $A$: cross sectional area of the bed (m²)
- $d_i$: diameter of particle of size i (μm)
- $d_p$: mean diameter of particle (μm)
- $F_p$: fine particle feed rate (kg/s)
- $H$: relative humidity of fluidization gas (-)
- $K$: elutriation rate constant (kg/m² s)
- $L$: bed height (m)
- $L_{mf}$: bed height at minimum fluidization velocity (m)
- $Q$: volume flow rate of fluidized gas (m³/s)
- $R_p$: elutriation rate of fine particles (kg/s)
- $U$: superficial gas velocity (m/s)
- $U_{mf}$: minimum fluidization velocity (m/s)
- $W_{co}$: weight of coarse particles (kg)
- $W_p$: weight of fine particles (kg)
- $X$: holdup of fine particles in the bed (-)
- $\bar{t}_a$: average residence time of fluidized gas in the bed (s)
- $\bar{t}_p$: average residence time based upon the average diameter of fine particles (s)
- $\rho_p$: density of particles (kg/m³)
- $\varepsilon$: void fraction of fluidized bed (-)
- $\varepsilon_{mf}$: void fraction at the minimum fluidization velocity (-)

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His major research field is the reaction engineering especially fluidization engineering. He invented new type of fluidization for the treatment of very fine particles, that is, powder particle fluidized bed (PPFB). Fundamentals and the application of PPFB is his recent major research works.