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Multilayer adhering model for holdup and separation behavior of fine particles in a powder-particle fluidized bed

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ABSTRACT

Time variation of the holdup of fine particles in a powder-particle fluidized bed was formulated on the basis of a multilayer adhering model. Unsteady-state experiments using a fluidized bed of 550 μm-silica sand, limestone, and glass beads were conducted under different operating conditions, changing the inlet concentration of aerosol fines (aluminum hydroxide), superficial gas velocity, and particle size of the fines (0.5 to 3 μm). The multilayer adhering model provided nearly the same value as that experimentally obtained. The model was modified so as to interpret numerous separable layers, which were subjected to being removed as fine-particle agglomerates. A change in the mechanism of the elutriation of fine particles with the size of fine particles was explained.

1. Introduction

A powder-particle fluidized bed (PPFB) [1] is one of the techniques for fluidization of fine particles of smaller than 30 μm, which is categorized as Group C in the Geldart classification [2]. A central feature of the PPFB is that a stable gas–solid fluidized bed of coarse particles (Group B) plays an important role for the dispersion of fine particles (Group C), adhering them on each coarse particle during fluidization.

A PPFB itself is also a good solid aerosol generator [3–7], in which the fluidized coarse particles disintegrate feed agglomerates of solid fine particles to almost single particles or small pieces of agglomerates to facilitate uniform elutriation to the gas phase. Conversely, a fluidized bed of coarse particles also provides a collection field for solid aerosol fines by offering a large amount of net surface area on which aerosol fines can adhere [8–10]. These opposite characteristics occur from the adhesion and re-entrainment behaviors of fines, which primarily depend on the size of fine particles.

Elutriation of solid fine particles can also be influenced by the properties of coarse particles in the PPFB [11]. However, the detailed mechanism to explain the relationship between the elutriation of fines from a PPFB and the holdup of fines in the bed has still remained unclear. Most of the earlier studies related on fluidized bed filtration have ensured essentially complete retention either by using a liquid aerosol [12,13] or by making a thin layer of a nonvolatile liquid on the surface of the collector particle [14]. A mathematical model was even established for simulating particulate removal in a gas–solid fluidized bed, assuming that the collected particulates were not re-entrained [15].

Our previous experimental study revealed that under the conditions of unsteady, adhesion-dominating state, a penetrating fraction of aerosol fines is no longer represented as a first-order function of the holdup of fine particles in the bed [11]. This means that the mechanism of penetration of fine particles through a bed of coarse particles is rather complicated, and it can be represented as a function of the surface coverage of coarse particles. In such a situation, it can be reasonable to think that fine particles in a PPFB are fluidized by forming multilayers on the surface of coarse particles.

This study aims to explain the behavior of aerosol fines in a PPFB by modeling the mechanisms of holdup and separation processes. Time variation of the holdup of fine particles in the bed is formulated on the basis of a multilayer adhering model.

2. Experimental

2.1. Materials

Various types of coarse particles, silica sand, glass beads, and limestone, with a mean diameter of 550 μm (sieving range is 500–590 μm) (Geldart B particles), were used in this study. Minimum fluidization velocity, U_{mf}, was calculated using the correlation of Wen and Yu [16]. Aluminum hydroxide particles with mean diameters of 0.5, 1, and 3 μm (C-3005, C-301, and C-303, Sumitomo Chemical Co., Ltd.) (Geldart

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Table 1
Physical properties of coarse and fine particles.

Code	Type of solid	ρ_p [kg/m^3]	d_p [μm]	U_{mf} [m/s]	$U_t \times 10^3$ [m/s]
Coarse particles					
SS550	Silica sand	2650	550	0.26	4510
LS550	Limestone	2750	550	0.27	4630
GB550	Glass beads	2500	550	0.25	4340
Fine particles					
AH005	$Al(OH)_3$	2400	0.5	–	0.018
AH01	$Al(OH)_3$	2400	1.0	–	0.072
AH03	$Al(OH)_3$	2400	3.0	–	0.65

C particles) were used as fine particles. The physical properties of coarse and fine particles are listed in Table 1.

2.2. Apparatus and procedure

Fig. 1 shows a schematic diagram of the experimental apparatus. The apparatus consists of a gas-humidity controlling system, a fluidized-bed solid-aerosol generator (Column A) equipped with a powder feeder (GMD-60, Gericke GmbH-Hosokawa Micron Co.), a PPFB column (Column B), and a gas–solid separator with a cylindrical bag filter. Columns A and B have the same inside diameter of 0.10 m and a height of 0.70 m and 0.85 m, respectively. The inside of the columns was coated with an antistatic agent (SP-2002, Colcoat Co., Ltd.).

Column B has a perforated plastic plate as a gas distributor, with 5 mm thickness and 3 mm holes arranged in a square, providing 5.7% opening area. A dispersion chamber with the same inside diameter as Column B and 0.35 m height was connected underneath the gas distributor to generate excellent aerosol dispersion before entering the gas distributor.

Vibrations were transmitted on the dispersion chamber as well as on a flexible hose connecting Columns A and B to minimize the adhesion of aerosol fine particles. Air with a relative humidity of 50% was used to minimize any electrostatic forces acting on the bed particles [17].

The fines penetrating through the PPFB in Column B were captured with a bag filter. Total amounts of the bed particles in Column B, the fine particles that adhered underneath the gas distributor during the run, and the fine particles that penetrated through Column B were measured after a halt of the run by shutting off the gas supply and powder feeding. The halt was made by removing manually the flexible hose at the inlet of Colum B. The bed particles, most of which fell through the orifices of the gas distributor by gravitation, were received by a stainless vessel put in advance near the bottom of the dispersion chamber. Details of the experimental apparatus and procedure are described elsewhere [11]. In this study, each run is represented in each plot in the results. Table 2 shows the experimental conditions.

2.3. Variables

To facilitate the establishment of mathematical models, the definition of the holdup of fines in the bed, X, after each run differs slightly from the one in the previous study [11], and is expressed as

$$X = W_{fp}/W_{cp} = \left(W_t - W_{cp}\right)/\left(W_t - W_{fp}\right), \tag{1}$$

where W_{fp} and W_{cp} are the amounts of fine and coarse particles in the bed, respectively.

The penetrating fraction of fines, λ, at each X is calculated from the mass balance for aerosol fines, namely

$$\begin{aligned}\lambda &= C_{out}|_m / C_{in}|_m = \left(C_{out}|_m Q\right)/\left(C_{in}|_m Q\right)\\ &= \left(R_{fp}\big|_m - R_{fp}\big|_{m-1}\right)/\left\{\left(W_{fp}+R_{fp}\right)\big|_m - \left(W_{fp}+R_{fp}\right)\big|_{m-1}\right\},\end{aligned} \tag{2}$$

where C_{in} and C_{out} are the concentration of aerosol fines at the inlet and outlet of Column B, respectively, Q is the flow rate of the fluidizing gas, and R_{fp} is the total weight of the fines that penetrated through Column B from the first run. The character m represents the m-th run in the experiment. The runs were continued until λ reached a stable value (near unity).

3. Model analysis

As a first step for theoretical analysis, the probability of aerosol fines to be held up in the bed, $(1 - \lambda)/\lambda_{max}$, is assumed to be proportional to

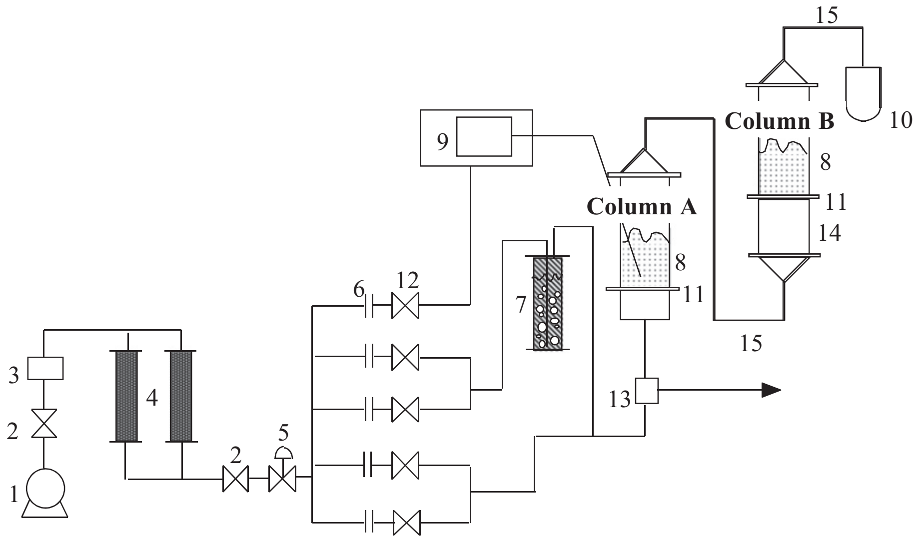

Fig. 1. Schematic diagram of experimental apparatus: (1) compressor, (2) gate valve, (3) oil filter, (4) silica-gel column, (5) regulator, (6) orifice meter, (7) humidifier, (8) PPFB, (9) powder feeder, (10) bag filter, (11) gas distributor, (12) glove valve, (13) ball valve, (14) dispersion chamber, and (15) flexible hose.