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Entrainment characteristics of fine particles in fluidized bed under preheating conditions

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ABSTRACT

The entrainment characteristics of fine silicon particles from solid mixtures (Geldart groups C and B) are investigated in a cylindrical fluidized bed with an inner diameter of 30 mm and a height of 450 mm and that is equipped with an agitator and an electromagnetic vibration table. Silicon particles (mean size of 2.7 μm) are used as entrained materials (group C), hollow alumina pellets (mean size of 1200 μm) are used as coarse particles (group B), and nitrogen gas is applied as carried gas. The effects of the superficial velocity of nitrogen gas at room temperature (U, 0.39 m/s to 0.98 m/s), the initial loading quantity of fine particles (M, 5 g to 20 g), the vibration intensity (Γ, 1.3 to 4.83), the stirring speed of agitator (V, 75 rpm to 195 rpm), the mass ratio of coarse to fine particles (N, 0 to 1.5), and the preheating temperature of nitrogen gas (T, 20 °C to 170 °C) on the entrainment characteristics (entrainment rate W_i and entrained powder–gas ratio R) are experimentally studied under atmospheric pressure. Significance analyses of U, M, Γ, and V are performed via the analysis of variance. M and U both significantly affect W_i, but only M significantly affects R. The experimental results show that an increase in U, M, N, and T constantly improves the entrainment characteristics, an increase in Γ deteriorates such characteristics, whereas there exists an optimal value for V to obtain the optimum entrainment characteristics. This study also determines that an optimal operating condition can result in optimal entrainment characteristics (W_i, 9.27 g/min and R, 0.19 g/g), which can be achieved with a U of 0.98 m/s, M of 20 g, Γ of 1.3, V of 155 rpm, N of 1.0, and T of 170 °C.

1. Introduction

Based on the fluidization technology and nitriding reaction of fine silicon powder, a fluidized bed reactor imposes strict requirements on raw silicon powder particle size for preparing fine silicon nitride powder at the micron level, which in turn requires the production of less agglomerations or the breaking of silicon aggregates in the fluidized process [1–3]. The dispersed cloud of powder feeding into the fluidized bed reactor must satisfy the following requirements: 1) low velocity to extend the residence time in the reactor; 2) small size to complete the conversion within a reasonable period; and 3) high powder–gas ratio to obtain high production efficiency and gas utilization [4]. Various feeders can be used for the feeding of powder, including mechanical feeders [5,6], pneumatic feeders [7], and fluidized bed feeders [8,9], but each of these feeders deals with specific types of materials. For example, the mechanical feeder is limited to medium-sized particles and tends to plug if used in transporting fine powder. The pneumatic feeder fits in a large-scale system, but has a high gas consumption and low powder–gas ratio. The fluidized bed feeder facilitates the aerated feeding of medium-sized particles to fine solids because of its high powder–gas ratio, simple construction, uniform flow rate, and favorable operability. In some applications of fluidized bed, such as combustion and catalytic cracking, the particles entrainment tends to be limited, which is considered an advantage in fluidized bed feeders [10].

The fluidized entrainment of fine particles presents a challenge to industry research. Geldart classified fine particles as group C particles [11]. A single fine particle cannot remain stable because of its extremely small size (less than 20 μm) and relatively large specific surface area. In this case, fine particles tend to agglomerate to achieve stability [12]. Group C particles also tend to agglomerate in the fluidized entrainment process, thereby reducing their fluidized quality. Therefore, group C particles are also known as cohesive particles. During the fluidized process, friction and collision continuously occur between group C particles, thereby reducing the distance among them. The van der Waals force emerges when such distance reaches the van der Waals distance scope. The friction between particles also produces static electricity [13,14]. The liquid bridging force is produced by the water in the fluidized gas, and all these forces will lead to the agglomeration of group C particles [15]. Therefore, many researchers have proposed various methods for preventing the agglomeration of group C particles or

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crushing the aggregates of these particles. These methods can be classified into three categories. The first category preprocesses the particles to eliminate the effects of the liquid bridging force, such as drying and surface modification [16]. The second category adds coarse particles along with fine particles to improve the fluidization characteristics of the latter by crushing their aggregates through collisions. The third category adds force fields to the fluidized bed, including vibration, stirring, sound, and magnetic fields, to counteract the viscous force among the fine particles and to reduce their agglomeration [17–20].

To determine the influence of coarse particles on the entrainment characteristics of fine particles, Yang et al. [19] investigated the entrainment characteristics of Geldart group C powder from solid mixtures (groups A and C) in a fluidized bed (with an inner diameter of 40 mm and a height of 150 mm) equipped with two vibrators and an agitator. Shin et al. [21] investigated the entrainment characteristics of fine powder from solid mixtures (Geldart groups A and C) in gas–solid fluidized beds with or without a tube.

A set of entrainment devices of silicon particles is designed to study the entrainment characteristics of fine silicon particles and their influencing factors as well as to achieve the high transportation concentration and efficiency of fine silicon particles. Industrial silicon particles and hollow Al_2O_3 pellets are used as raw materials. Vibration, stirring, and coarse particles are added to the fluidized bed to study the effects of the superficial velocity of nitrogen gas at room temperature U, initial loading quantity of fine particles M, vibration intensity Γ, and stirring speed V on the entrainment characteristics of fine silicon particles. A variance analysis of the four factors (U, M, Γ, and V) is performed according to the calculated orthogonal experimental results. The effects of the mass ratio of coarse to fine particles N and the preheating temperature of nitrogen gas T on the entrainment characteristics of fine silicon particles are then studied based on the control variables in the experiment. The optimal entrainment operating conditions of fine silicon particles in the cylindrical fluidized bed are eventually determined.

2. Experiment material and methods

2.1. Experimental apparatus and procedure

The experimental apparatus, which comprises a gas supply system, temperature control system, fluidized bed, vibration table, agitator, and bag filter, is schematically shown in Fig. 1. The gas supply system comprises a gas cylinder, regulating valve, flow meter, and preheater. Gas flow can be regulated using the regulating valve. The preheater has a rated power of 1.5 kW. The temperature control system comprises a regulator, thermocouple, and paperless recorder. Through the paperless recorder, the temperature of gas in the fluidized bed can be recorded by the K-type thermocouple. The body of the fluidized bed includes a stainless steel column with a 30 mm inner diameter and 450 mm height. The distributor is a perforated stainless steel plate with an aperture of 1 mm and an opening area ratio of 6.69%. A 1000 mesh screen is used to cover the surface of the distributor to prevent powder from leaking into the plenum chamber. An agitator is fixed on the top of the bed, and a stirring bar (445 mm in length and 26 mm in profile diameter) is attached on the agitator. The entire fluidized bed is fixed on the electromagnetic vibration table, and the entrance of the fluidized bed is connected to the preheater. The export of the fluidized bed is connected to the bag filter, which has a favorable collection efficiency effect on the entrained powder in the experiment.

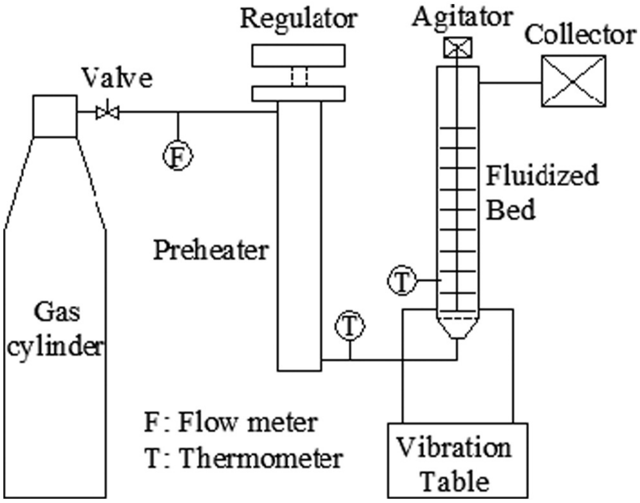

Fig. 1. Fluidized entrainment apparatus of fine silicon particles.

The experimental procedure is explained in the succeeding paragraph. Silicon particles and alumina pellets are placed in an incubator at 105 °C for 24 h to remove the absorbed water. The gas supply and temperature control systems are activated, and the temperature of gas in the fluidized bed is set to a predetermined value. A weighed quantity of premixed silicon particles and alumina pellets are introduced into the bed. The flowmeter, vibration table, and agitator are set to predetermined values. The bag filter is weighed using an electronic balance with a 0.001 g accuracy (denoted as m_1). The experiment begins after turning on the valve, vibration table, and agitator. After 5 min, the entire apparatus is switched off, and the bag filter is reweighed (denoted as m_2). These procedures are repeated thrice in each experiment, and the average value is used as the final value for calculating the entrainment characteristics.

2.2. Experimental materials

Fine silicon particles are used as the entrained materials, hollow Al_2O_3 pellets are used as the coarse particles, and industrial nitrogen gas (99.5% purity) is used as the carrier gas. Table 1 lists the physical properties of the silicon particles and Al_2O_3 pellets. The minimum fluidization velocity (U_{mf}, m/s) and terminal velocity (U_t, m/s) at 20 °C are calculated using the formulas in [22]. The size distributions and SEM images of the fine silicon particles are shown in Figs. 2 and 3, respectively.

2.3. Experimental design

The effects of U, M, Γ, V, N, and T on the entrainment characteristics of the aforementioned entrainment apparatus are studied. The experimental factors are set as follows: U is 0.39, 0.59, 0.79, and 0.98 m/s; M is 5, 10, 15, and 20 g; Γ is 1.3, 2.46, 3.6, and 4.83; V is 75, 115, 155, and 195 rpm; N is 0, 0.25, 0.5, 1, 1.25, and 1.5; and T is 20 °C, 39 °C, 68 °C, 106 °C, 126 °C, and 170 °C.

Among all factors, Γ is a dimensionless number defined as follows:

$$\Gamma = A\ (2\pi f)^2/g, \tag{1}$$

where A(m) and f (Hz) are the amplitude and frequency of the vibration, respectively, and g(m/s^2) is the gravimetric acceleration.

Entrainment rate W_i is defined as follows:

$$W_i = (m_2 - m_1)/\Delta t \tag{2}$$

where W_i(g/min) is the entrainment rate, m_1(g) and m_2(g) are the mass of the bag filter at the beginning and end of the experiment, respectively, and Δt(min) is the duration of the experiment.

The mass ratio of entrained powder to the needed nitrogen gas (i.e., entrained powder–gas ratio) R is defined as follows:

$$R = \frac{60 \times W_i}{1000 \times U \times S \times \rho} \tag{3}$$

where R(g/g) is the entrained powder–gas ratio, U(m/s) is the superficial velocity of nitrogen gas at room temperature, S(m^2) is the cross-