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Experimental study on fluidization of fine powders in rotating drums with various wall friction and baffled rotating drums

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ABSTRACT

Fine powders were found to be fluidized in a rotating drum by internal cycling gas by the drum rotation. It is essentially a fluidized bed without requiring any external fluidizing gas. Such a rotating drum can be regarded as a new gasless fluidized bed for fine powders in contrast to a traditional fluidized bed, possibly leading to a considerable amount of energy savings. In addition, the fluidization quality of fine powders was found to be further improved with the assistance of drum rotation because of the shearing movement among particles that eliminates channeling and cracks and possibly also breaks agglomerates. Five regimes were identified in the rotating drum including slipping, avalanching-sliding, aerated, fluidization and re-compacted regimes. It was also found that drum wall friction plays an important role to fluidize fine powders because the friction carries particles to the freeboard, leading to gas cycling that fluidizes the powders. As well, three types of specially designed baffles were utilized to promote powder fluidization in rotating drums. These baffles effectively bring an early onset of all the regimes in rotating drums by reducing powder–wall slipping, carrying particles and bringing additional gas to the powders.

1. Introduction

Fluidization occurs when particulate materials are suspended in up-flowing gas. It is a preferred mode of operation if the gas and powder need to be brought into good contact, due to its special characteristics: uniform and extensive gas–solid contact, good solids mixing, uniform temperature, high mass and heat transfer rates, easy solids handling, etc. However, a traditional fluidized bed needs a large amount of gas flowing continuously through the bed to balance the particle gravitational force so that powder would stay fluidized. This is tolerable for a reaction process, in which the fluidizing gas is a reactant as well. But for some physical processes (i.e. mixing), it is a large energy waste for a large amount of fluidizing gas to be compressed and blown into the fluidized bed only to keep the powder fluidized. It would be beneficial to have a process that incorporates the advantage of fluidization with less or no gas and reduced energy consumption.

Generally, coarse powders (Geldart group A and B powders) can be well fluidized in a traditional fluidized bed; however, it is difficult for fine powders (Geldart group A/C and C powders) to be fluidized due to their cohesive nature, leading to agglomerating, plugging and channeling (Geldart, 1973). As such, fine powders have not been employed widely although they are often preferred for various applications because of their large specific surface area. Several decades ago, people began to fluidize fine powders by applying some additional aids. These fluidization aids can generally be divided into two categories: one is to introduce external energy into the fluidized bed system to break powder agglomerates and channeling, such as mechanical stirring (Nezzal et al., 1999), mechanical vibration (Dutta and Dullea, 1991; Mori et al., 1990), acoustic waves (Montz et al., 1988) and magnetic or electrical field disturbance (Liu et al., 1991). The other category is to perform surface modification of particles to reduce their cohesiveness such as gas adsorption (Geldart and Abrahamsen, 1978; Xie, 1997) and adding smaller particles as flow conditioners (Castellanos, 2005; Dutta and Dullea, 1990; Zhu and Zhang, 2004).

Fine powders also exhibit different behaviors from coarse powders in another operation mode—a rotating drum. Rotating drums have been widely used in industry for drying, mixing and segregating grains (Cooke et al., 1976), but not as means of fluidization. As well, behaviors of a coarse powder in the rotating drums have been well studied (Baumann et al., 1995; Franklin and Johanson, 1955; Henein et al., 1983; Jaeger et al., 1989; Mellmann, 2001; Rajchenbach, 1990; Tang and Bak, 1988). Generally the powder experiences surging, slumping, rolling, cascading cataracting and centrifugal motions as drum rotation speed increases (Henein et al., 1983; Mellmann, 2001), without fluidization being observed. However, the preliminary study by two research groups showed it is possible for a fine

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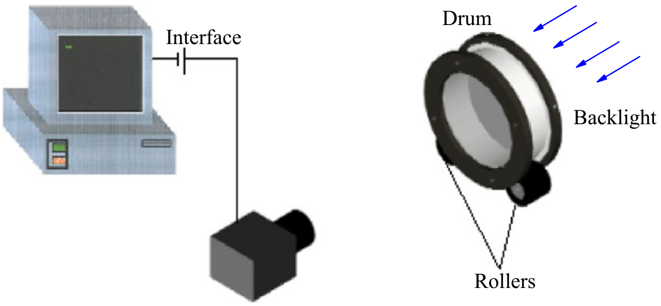

Fig. 1. Schematic diagram of revolution powder analyzer system.

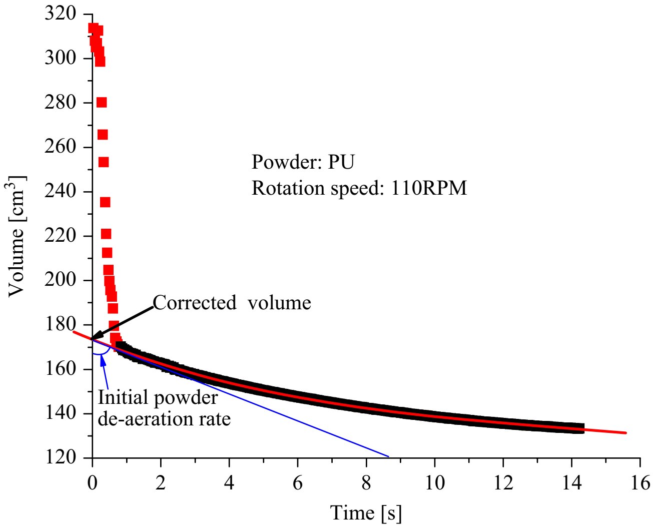

Fig. 2. De-aeration procedure of PU powder rotating at 110 rpm.

powder to be fluidized in the rotating drum. Rietema (1991) studied the fluidization in “a ball mill without balls” and proposed the following qualitative fluidization criterion to predict the minimum fluidization of a fine powder. He suggested that the fine powder is fluidized when the time that continuity waves of gas reach the powder free surface from the bottom is larger than the time that the rotating drum wall carries the layer of settled down powder away.

$$N_g = \frac{\rho_d g d_p^2}{\mu V_a} \leqslant 60 \frac{h}{L\varepsilon^2} \qquad (1)$$

where ρ_d and d_p are particle density and diameter, ε is the porosity of the powder bed, and μ is the viscosity of gas, h is the height of the powder bed, L is the part of the drum wall covered by the powder and V_a is the circumferential velocity of the rotating drum. Although the minimum fluidization angular velocity can be solved according to Eq. (1), it is actually difficult to estimate the value of ε and h/L without experimental measurements.

Castellanos et al. (2001) reported fluidization of polymer-based toner of 12.7 μm in several rotating drums of various dimensions. They employed the ratio of the length of the flat powder surface (d) to the drum inner diameter (D) and the ratio of the powder volume to the initial filling volume as indicators of fluidization. When powder is fluidized, the powder free surface would appear flat like fluid and the volume of the powder would show significant expansion. Accordingly, the powder is completely fluidized when the length of the flat powder surface is close to the drum diameter ($d/D \approx 1$). However, d/D should also depend on the initial load of powder and drum size, which was ignored in their study. Castellanos et al. (2002) also proposed a physical model to describe powder behaviors in rotating drums.

In this study, behaviors of the fine powder in a rotating drum were comprehensively studied and summarized. In particular, its fluidization was compared with the fluidization in a traditional fluidized bed. Additionally, the drum wall was coarsened to study the effects of wall–powder friction on powder behaviors. It was found that the fluidization of fine powder was improved by higher wall–powder friction. Furthermore, three types of specially designed baffles were used to promote powder fluidization, and they were found to be very effective.

2. Experimental methodology

The apparatus employed in this study was a Revolution Powder Analyzer manufactured by *Mercury Scientific Inc*. It consisted of a rotating system with an image capturing and analysis system as shown in Fig. 1. The rotating drum was made of aluminum with an inner diameter of 110 and 35 mm in width. The two sides were covered with transparent Plexiglas, so the behavior of powder inside could be captured by the image capturing system. The drum was rotated by two high precision silicone rollers controlled by a step motor, which accurately controlled the rotation speeds of the drum in a range from 0.1 to 200 rpm. A digital camera, with the assistance of backlight illumination, captured images at a rate up to 30 frames per second. All collected images were saved on a computer and analyzed by software offered by the manufacturer. It recognized particles on images and then counted their pixels, based on which it calculated some parameters such as powder volume, the lowest height and angle of the powder surface.

In each test, a powder was filled in the drum and rotated at a high rotation speed of 100 rpm first to induce fluidization for a period of time so that the agglomerates formed during the storage or other handling processes were broken and a repeatable state was reached. Then rotation was stopped and the powder settled down until the volume of the powder reached a constant level. The drum was then rotated at a very low speed of 1 rpm, at which the volume of the powder was measured as initial powder volume in a test. Then the drum was set to rotate at various rotation speeds; for each condition, 600 measurements of powder volume and height were taken when a steady state was reached and their averages were recorded as test volume. At the same time, all images were saved in a computer.

When the drum bed is operating at high rotation speeds, the powder is fluidized and meanwhile a large amount of particles are carried up by drum wall and then tossed in the freeboard as a shower. As a result, there is no significant difference of contrast between the freeboard and the powder bed. In addition, fluidizing gas forms bubbles and these bubbles burst at the powder bed surface leading to a vague interface as detected by the camera. The system would count all the projected area as powder area and thereby overestimates the powder volume. To properly measure the powder volume at high rotation speeds, bed collapse technology was employed. Powder was first rotated at a rotation speed to reach a steady state, then the drum was stopped suddenly, and the powder volume with respect to time was recorded as shown in Fig. 2. The volume decreased very quickly at the beginning when all tossed powder fell back down to the powder bed. Afterwards, the whole powder demonstrated a de-aeration procedure while gas in the powder was gradually escaping away. It is reasonable to believe the large decrease of volume was caused by the overestimate. Consequently, a best fit of the de-aeration curve was extrapolated to the y axis (time = 0 s) and the value of the intersection point was taken as corrected powder volume, a similar approach as estimating the dense phase volume in a fluidized bed by employing bed collapse technique (Rietema, 1967). Fig. 3 shows a comparison of recorded volume calculated by the software and the