PARTICLE AGGLOMERATION CHARACTERISTICS IN VIBRO-FLUIDIZED BED DRYERS

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Key Words: Drying, Particle Agglomeration, Fluidization, Vibro-Fluidized Bed, Ammonium Perchlorate

Introduction

In the chemical and process industry, vibro-fluidized beds (VFB) have found particular application in drying easily agglomerated materials, sticky powders (or particles) and particulate solids consisting of large particles with wide particle size distribution. These wet agglomerated and/or sticky particles generally are difficult to fluidize in a conventional fluidized-bed dryer. Vibro-fluidized bed drying, however, is considered as one of the more useful types for drying such wet particles since the VFB can enhance the fluidity of the bed through addition of vibration to the bed; this makes the bed much easier to fluidize even under a lower superficial air velocity

Fluidized bed dryers include better homogeneity, gentler handling, better control of residence time distribution, and improved heat and mass transfer rates. Considerable improvement in the fluidity of wet particles in a VFB helps overcome interparticle attraction forces. Generally, for wet particles with diameters of several tens of micrometers or larger, the interparticle attraction forces are primarily due to liquid bridges. If static dryers are used to dry crystalline particles which are partly soluble in the liquid of the liquid bridges, solid bridges will form due to interparticle crystallization. In other words, after an improper drying the particles stick together and behave as clusters consisting of two or more particles, and this particle agglomeration leads to a larger particle size distribution which is usually not desirable. To our knowledge, most of the published
papers concerning VFB drying have concentrated on studies of heat and mass transfer improvement. In the present investigation, however, we tried to determine whether or not VFB drying is effective in preventing particles from agglomeration during the drying of easily agglomerated particles. Particle agglomeration characteristics were studied by using both a “high-amplitude vibro-fluidized bed” (HA-VFB; vibration amplitude is 3.8 cm) and a “low-amplitude vibro-fluidized bed” (LA-VFB; vibration amplitude is 0.26 cm). The influence of the operating variables including vibration intensity, vibration amplitude, and air inlet temperature on particle agglomeration characteristics were experimentally examined.

1. Experimental

A flow diagram of the experimental apparatus used in this study is shown in Fig. 1. The heart of the apparatus is two fluidization chambers of 20 cm inside diameter and 15 cm height. The exterior walls of the chambers were covered with heat insulation. An inverter was used to vary the vibration frequency of the VFB dryers. The frequency of vibration was measured by a tachometer. The air inlet temperature was controlled by an SCR controller. The air distributor was a perforated plate (0.3 cm-diameter holes distributed on square pitch of 2.5 cm) which was covered with a 400-mesh stainless steel wire net. The distance between the perforated plate and the wire net was 1 cm. On the top of each chamber, a plexiglass plate with a 5.08 cm-diameter wire net at the center was used to reduce the carry-out of particles and permit visual observation.

In this study, the wet AP layer thickness (bed height) was kept at about 1 cm, which is relatively thin, to assure intimate contact of air with all particles and no measurable degradation of particles. Thin layers are normally encountered in industrial VFB dryers operated in continuous mode because maximum particle suspension is thus attained and maximum heat exchange results. The samples used were wet ammonium perchlorate (AP) crystalline particles characterized as nearly spherical with median particle sizes of 250–270 μm, and with either water or isopropanol (IPA) liquid films on their surfaces. These wet particles were prepared from a cooling crystallization process, in which AP crystalline particles crystallized out of an AP aqueous solution. After separation of the AP particles from the mother liquor, the moisture content of the water film on the particles was about 2.1 wt%. If necessary, some of the water-surface particles were further washed with an IPA solution which was pre-saturated with AP at room temperature. After the IPA wash, the AP particles were filtered and the moisture content of the IPA film on the particles was determined to be about 2.3 wt%.

While the air flow and the air inlet temperature reached steady state, we turned on the vibrator and adjusted its frequency, and then the weighed wet sample (500 g) was introduced. After drying for 15 minutes the time necessary to remove the surface moisture of the particles even though the bed was not vibrated, the bed was cooled to 40°C and the dried particles were collected for size-distribution measurement, which was made by a vibro-sieving machine that determined the weights of particles sieved in eight size ranges: <150, 150–180, 180–250, 250–300, 300–355, 355–425, 425–500, and >500 μm.

For all the experiments, the air flow rate was 0.0105 m³/s, which is equivalent to a superficial air velocity of 33.3 cm/s at 25°C. After VFB drying the degrees of particle agglomeration were interpreted in terms of the shift of particle size distributions or the variation of median particle sizes. The ranges of the operating parameters examined were: vibration frequency (0–29 Hz), amplitude (0.26 cm for the LA-VFB and 3.8 cm for the HA-VFB), and air inlet temperature (40–100°C).

2. Results and Discussion

The solubility of AP in water increases linearly with increasing solution temperature, as has been previously determined by Ayerst. The solubilities at temperatures 20, 40 and 80°C are 17.9, 25.6, and 40.4 g/100 g solution respectively. At 20°C the solubility of AP in IPA is 0.69 g/100 g solution, which is very limited and is negligible compared to its solubility in water. In the study of particle agglomeration characteristics it is desirable to measure the particle size distribution of the wet particles as a reference. For that reason we used IPA washed particles as the drying sample. After drying the sample, it was assumed that particle agglomeration should be negligible since almost no AP material could crystallize between the particles. This assumption was proved by observations under a photomicroscope. Thus the particle size distribution of the dried particles should
be the same as that of the wet particles before drying.

For sinusoidal vibration of a vessel at a frequency \(f(\text{Hz})\) and a peak amplitude \(Z_0\), the dimensionless vibration intensity \(K^{14}\) is the ratio of peak vessel acceleration to gravitational acceleration \(g\), and is defined as \(Z_0(2\pi f)^2/g\). Prior to the drying experiment, minimum fluidization velocity \(U_{mf}\) was determined by using LA-VFB with vibration intensity \(K=8.3\) or 0. Dry AP particles were used for the bed the height of which was 1 cm. The plot of bed pressure drop vs. air velocity for both the VFB \((K=8.3)\) and the CFB (conventional fluidized bed also known as non-vibrated bed and thus \(K=0\)), shown in Fig. 2, reveals that \(U_{mf}\) is roughly independent of \(K\), and the \(U_{mf}\) is 29 cm/s at 25°C. Further, the pressure drop of the VFB is lower than that of the CFB over the entire range of operating conditions used in this study. In the following experiment, the superficial air velocity was controlled at 33.3 cm/s in order to operate in the fluidized-bed region and to avoid particle fly-off. If the superficial air velocity is much larger than 33.3 cm/s, an appreciable carry-out of the drying particles from the fluidization chamber will occur.

It should be noted that wet AP particles for each parametric study described below were prepared from different crystallization batches. Therefore, the wet samples for each parametric study possibly represented different particle size distributions. Furthermore, considerably scattered data were obtained in the experiments and this may be due to the nonuniformity of particle size distribution of wet samples, even those coming from the same crystallization batch.

### 2.1 Effect of vibration intensity of particle agglomeration

The effect of vibration intensity on particle agglomeration after HA-VFB drying is shown in Fig. 3, where the wet samples were with the water films and the air inlet temperature was 60°C. Although wet AP particles were nearly spherical, they tended to agglomerate through liquid bridges and therefore showed poor fluidity. When HA-VFB drying was operated at a lower vibration intensity \((K\) approaches 0), the bulk of the bed moved as a whole with hardly any interparticle mixing, and the drying process was the same as in a through-flow drying. In this case, since there was almost no relative motion between neighboring particles at early stages of drying, it was deduced that during drying the transition from liquid bridges to solid bridges could be completed without any mechanical disturbance, leading to a greater extent of particle agglomeration. On the other hand, when HA-VFB drying was operated at a higher vibration intensity \((K \geq 7)\), particle agglomeration was significantly retarded. This is perhaps because under such vigorous particle mixing liquid bridges were cut as soon as they were initiated, thereby hampering the transition to solid bridges. The particle agglomeration characteristics in a vibro-fluidized bed could also be interpreted in terms of the variation of median particle sizes (the size corresponding to the 50% weight undersize in Fig. 3). Therefore Fig. 4 is another type of expression of Fig. 3, and this expression is used in the following discussion of experimental results.

In many fluidization processes, attrition of particles is a problem because it increases the number of particles and reduces particle size. In this investigation, however, attrition was negligible due to the following observations. (1) In Fig. 3, the % weight undersize for particles < 135 μm was about 1%. Further, the particle fly-off was less than 1%. These observations indicate that abrasion could be neglected. (2) After sieving, the
shape of dried particles observed under 2 photomicroscope was spherical. This observation shows that there was no breaking or splitting of AP particles.

2.2 Effect of vibration amplitude on particle agglomeration

Figure 5 shows that the median particle sizes of particles dried in either the HA-VFB or the LA-VFB dryer. Two kinds of wet samples were used. One was AP particles with surface films of water, and the other was AP particles with surface films of IPA. The air inlet temperature was 60°C. The drying experiments were carried out three times for wet samples stored over 1, 3, and 8 days respectively.

Although the dimensionless vibration intensity $K$ of the LA-VFB was slightly higher than that of the HA-VFB and their intensities were 8.3 and 7 respectively, the degree of agglomeration of particles dried by the LA-VFB was much greater than that of particles dried by the HA-VFB. During LA-VFB drying, it was observed that bed mixing was impaired since the bed moved as a whole. As drying proceeded, the fluidity of the bed particles increased since the particles became drier. When most of the surface moisture of the particles was removed, fast particle circulation as described by Savage was observed and the bed was fluidized. Despite the fluidization occurring in the later stages of LA-VFB drying, the degree of particle agglomeration was significant. In contrast with these results, when wet samples, with either water or IPA surface, were dried using the HA-VFB, the degree of particle agglomeration for these two kinds of samples seemed to be in the same range, and was almost negligible. The results described above appeared to indicate that when the particles were still wet, relative motion between particles was necessary for obtaining discrete dried particles. Moreover, as shown in Fig. 5, the degree of particle agglomeration varied widely for LA-VFB drying of samples stored over different periods. An assumption was considered that during the early stages of the LA-VFB drying the bed moved as a whole and wet AP agglomerates (formed over a short storage period, such as 1 or 2 days) were not able to be crushed until a fluidization occurred. Therefore, the LA-VFB drying could hardly give reproducible data of degree of particle agglomeration.

2.3 Effect of air inlet temperature on particle agglomeration

Figure 6 shows the relationship between median particle size and air inlet temperature for the HA-VFB drying experiments, in which the vibration intensity $K$ was 7. In this study of the temperature effect it was more difficult to obtain reproducible data than was the case in the studies of other effects described previously; the reason is not known at present. Each value of median particle size in Fig. 6 was thus an average value based on the results of three identical experiments. There seemed to be no apparent trend indicating that particle agglomeration could be significantly affected by changing the air inlet temperature, with the exception of drying at a high air inlet temperature such as 100°C (the boiling point of water at atmospheric pressure). When particles were dried at 100°C, rapid evaporation of surface moisture might have enhanced the buildup of solid bridges between particles in a short time, thus accounting for the higher degree of particle agglomeration (larger median particle size) obtained.

Conclusion

The HA-VFB dryer, with a vibration amplitude of 3.8 cm, operated in suitable conditions, has been demonstrated experimentally to be an effective dryer that prevents particle agglomeration. Based on the experimental results, three conclusions are drawn.

1) At the very beginning of VFB drying, relative motion between particles is necessary to secure discrete dried particles.

2) In the range of operating conditions studied, though the vibration intensity of the LA-VFB is higher than that of the HA-VFB the particles dried in the HA-VFB showed a lower degree of particle agglomeration than particles dried in the LA-VFB. This means that $K$ is not the only factor determining the degree of particle agglomeration. Both vibration
amplitude and frequency are equally important in preventing particles from agglomeration.

(3) The air inlet temperature should not be too high, because a higher degree of particle agglomeration might result.

Acknowledgement

The authors are grateful for research support provided by the Chung Shan Institute of Science and Technology and its permission to publish this work. We particularly want to thank Mr. S. L. Wang and Mr. S. M. Chang for technical assistance.

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