CHEMICAL ENGINEERING TRANSACTIONS
VOL. 43, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-34-1; **ISSN** 2283-9216
DOI: 10.3303/CET1543129

Dust Generation in Vibrated Cohesive Powders

Hamid Salehi Kahrizsangi, Daniele Sofia, Diego Barletta, Massimo Poletto*

Dipartimento di Ingegneria Industriale - Università di Salerno, *Via Giovanni Paolo II, 132 – 84084 Fisciano (SA) –Italy*
mpoletto@unisa.it

The process of dust release from aggregative cohesive powders under the action of mechanical vibration is studied. Beds of cohesive Potato Starch and Silica powders at fixed heights were vertically vibrated in a column in which vibration, frequency and acceleration levels can be independently set. Acceleration was changed with acceleration gravity ratio (a/g) values ranging between 5 and 9, while frequencies were set at 70 and 120 Hz. Vertical air flow rates through the bed were used to simulate air entrainment. Air in the head space above the bed was extracted and filtered in order to quantify the released dust rates. Results of these experiments are discussed and analyzed with reference to both the aggregative behavior of these powders and the inter-particle forces estimated from the bulk flow properties measured with conventional and standardized powder flow testers. A good relationship is found between the natural tendency of these powders to generate aggregates, the inter-particle forces and applied acceleration levels. Better insight of the physics is required to understand the effect of frequency on the dustiness of these powders.

1. Introduction

Production, trade and processing of fine powders require handling and transport of these materials that are prone to releases of airborne dust. The use of powders, fine to the nanometric scale, makes the control of the dust emission (Saleh et al., 2014) of primary importance to carry out safe operations (Grima-Olmedo, 2014). Control and prevention of dust emission require the understanding of the tendency of these powders to release dust (Faschingleitner and Höflinger, 2011) as well as the ability of modelling the process in order to quantify the amounts of the emitted dust (Wypich et al. 2005). Appropriate measuring sytems should be applied depending on the operation generating dust (Hamelmann and Schmidt, 2004).
Application of vibrations is often used to simulate the effects of transport on the dusts release (Saleh et al., 2014). However, a correct scale up of results requires a certain understanding on the fundamental physics involved in dust releases. In particular, it is necessary to relate the tendency of dust generation to the agglomeration behavior of fine and cohesive powders. In fact, on the one hand agglomeration determine the active surface generating dust emission, on the other hand it contain dust emission by means of cohesion. In this paper, the role of vibration on dust emission is studied in a fluidized bed assisted by mechanical vibrations. The aggregative analysis developed by Barletta et al. (2007) and applied by Barletta and Poletto (2012) to gas fluidized beds assisted by mechanical vibration is used to discuss the results.

2. Apparatus

A sketch of the apparatus, a vibrated fluidization column and a dust metering system, is reported in Figure 1.

2.1 Vibrated fluidization column

The fluidization column was made of perspex with an 85 mm ID and a height of 400 mm (1). At the bottom, the air was distributed by a 10 mm thick porous plate of sintered brass particles, 10 μm in diameter. The porous plate was clamped in the flange connecting the wind box and the fluidization column. In the column flange, a pressure port was connected to a u-tube manometer (6) filled with water. Desiccated air from the laboratory line was fed to the wind box by a thermal mass flow controller (Tylan FC2900V) with a maximum flow rate of

Please cite this article as: Salehi Kahrizsangi H., Sofia D., Barletta D., Poletto M., 2015, Dust generation in vibrated cohesive powders, Chemical Engineering Transactions, 43, 769-774 DOI: 10.3303/CET1543129

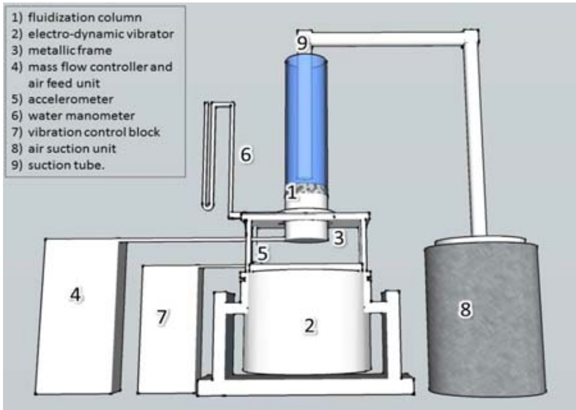

Figure 1: Experimental apparatus

5 10^{-5} std m^3 s^{-1} (0 °C and atmospheric pressure) (4). The column was fixed to the vibrating plane of the actuator by means of a rigid steel and aluminum structure (3). The actuator (2) was an electric inductance vibrator (V100 Gearing and Watson, USA) that was able to produce a sinusoidal vertical movement in the range between 2 and 6500 Hz with displacement amplitudes of up to 12.7 mm, exerting a maximum force of 26.7 kN. The vibrator amplifier was connected to a vibration controller Sc-121 (Labworks inc., USA) (7). The controller measures the effective vibrations by means of a piezoelectric accelerometer (8636B60M05 Kistler, USA) (5) fixed on the metal structure supporting the fluidization column.

2.2 Dust metering system

A system made of an air suction unit (8), a tube (9) and a filter was used to extract the dust released in the column headspace. The air suction system is connected to a 40 mm ID tube hold vertically and downward into the column freeboard. The tube holding stand is independent of the column and keeps the tube in its position during the bed operation. The holder allows to regulate the height of the tube tip over the bed surface. A poach of paper filter at the tube tip is used to capture dust.

3. Materials

Properties of the Silica and the Potato Starch powders used in the experiments are reported in Table 1. The rheological properties were measured with a Schulze ring shear tester (Schulze, 1994) with a partially modified apparatus (Tomasetta et al., 2011). Values of the powder cohesion, C, and of the angle of internal friction, ϕ_i, evaluated from yield loci at different consolidation are reported in Figure 2. Table 2 reports the values relevant to fluidization, C_0 (Figure 2a) and ϕ_{i0} (Figure 2b), which were obtained by extrapolating the value of these parameters to zero consolidation. Different particle size distribution, shape as well as material hardness are responsible for the flow property difference between the two powders as discussed by Tomasetta et al. (2013). Silica and Potato Starch powders were also used by Barletta and Poletto (2012) who found that these Geldart (1973) group C materials properly fluidize in form of aggregates if mechanically vibrated. It was also verified that the aggregate size, d_a, changes with the acceleration level of the imparted vibration. In fact, it was shown that the size is the one at which the inertia of the aggregate, subject to the vibrational acceleration, a, equals the force connecting the aggregate to the neighboring bulk of the material:

$$d_a = \frac{6}{k\pi}\frac{\sigma_{t0}}{a\rho_a} \quad (1)$$

where ρ_a is the aggregate density, set equal to the initial bed density; k is the number of the effective contacts between an aggregate and its neighbors on a close layer assumed equal to 3, like the number of contacts

Table 1: Material properties

Material	d_p μm	d_{p10} μm	d_{p50} μm	d_{p90} μm	ρ_p kg m^{-3}	ρ_{bv} kg m^{-3}	ρ_{b0} kg m^{-3}	C_{i0} Pa	ϕ_{i0} deg	σ_{t0} Pa
Silica	7.6	2.8	21	66	2650	1400	1020	43.3	36.7	43.4
Potato starch	21	23	46	80	1570	854	773	24.2	25.3	30.7

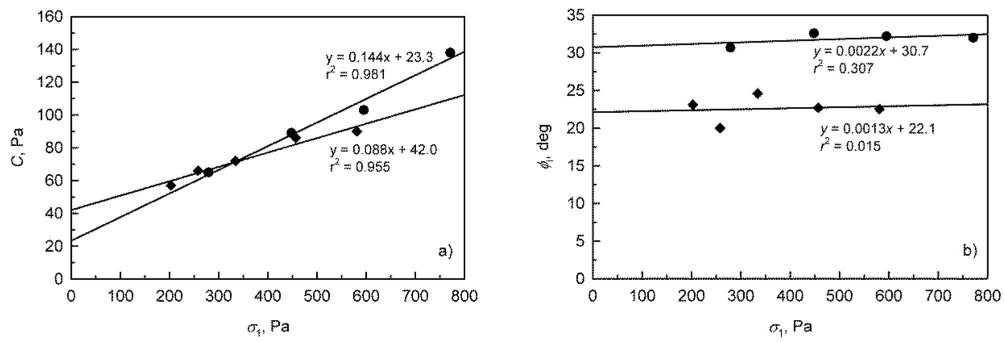

Figure 2: Cohesion a) and angle of internal friction b) at decreasing values of major principal stress during consolidation for: ◆, Silica; ●; Potato Starch

between a sphere and a neighboring layer of other spheres; σ_{t0}, is the tensile strength of the bulk material at zero consolidation calculated from the Eq. 2 which is valid for Coulomb materials:

$$\sigma_{t0} = -\frac{2C_0 \cos\phi_{i0}}{1+\sin\phi_{i0}} \tag{2}$$

4. Procedures

All fluidization experiments were carried out with beds of 0.3 and 0.225 kg of material for Silica and Potato Starch powders, respectively. Correspondingly, bed heights of about 50.8 mm and 50.1 mm were obtained for the two materials. Desiccated air was used as fludizing medium which allowed to keep the starch humidity constant during the experiments. No evident electrostatic effect could be detected, though the presence could not be excluded. Different acceleration values were used. These were conventionally referred to the acceleration due to gravity, *g*, and correspond to values of the acceleration ratio *a*/*g* between 5 and 9. In addition, frequencies were set to 120 Hz and 70 Hz.
When applying vibrations, the maximum acceleration, *a*, is related to the sinusoidal vibrating movement. Given the oscillation amplitude, *A*, the oscillation frequency, *f*, or the pulsation value, ω. It is:

$$a = A\omega^2 = A(2\pi f) \tag{3}$$

During dust emission experiments, the suction unit, the air feed unit and the vibrating system were turned on at the same time and let run for 30 s. Afterwards, the amount of captured dust was measured with an analytical balance. Filter clogging was excluded by verifying linearity with time of the collected solids amounts. All the provided dust capture results are averages of several repetitions made.

5. Results

Typical fluidization curves for these materials are reported in Figure 3. It appears a rather smooth fluidization with maximum pressure drops different from what expected by non-vibrated fluidization and bed expansion which starts before the attainment of constant pressure drops due to the energy introduced by vibrations. This peculiar phenomenology of fluidization of vibrated powders was discussed by Barletta et al. (2007).
For dust capture experiments, powders were fluidized at a fixed gas flow rate of 2.12 10^{-5} Nm^3 s^{-1}, corresponding to a fluidization velocity of 3.74 mm s^{-1} at which both material appear well fluidized. Only at high acceleration levels with Silica at 70 Hz some bubbling was observed. The appropriate height of the suction tube was identified to be 210 mm as the height above the bed surface at which the amount of captured dust did not change significantly with further increase of the tube height in absence of both air flow and vibration.
Figure 4 reports captured dust data. Each of the data point is the average of at least 10 independent tests and the error bars represent standard deviations within these tests. The material was changed and renovated at each new testing condition. In general. the curves show an increase of the captured dust with acceleration intensity. Almost the same quantity of dust were collected with the two materials at 70 Hz, while significantly lower amount of dust were collected when operating at 120 Hz. The intense dust collection for Silica at 70 Hz and above a/g=7 correspond to the bubbling bed experimental condition.

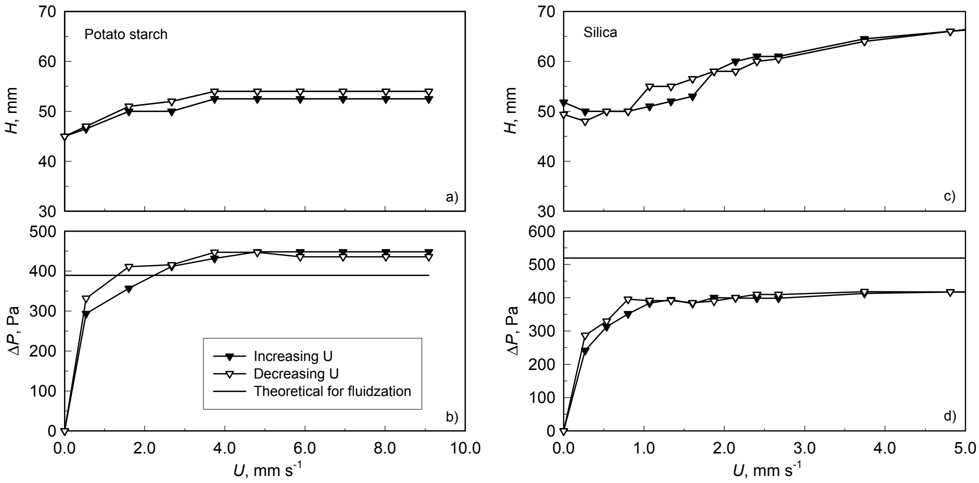

Figure 3: Fluidization (b and d) and bed expansion (a and c) curves at a/g=8. a) and b) 0.255 kg Potato Starch bed at 70 Hz. c) and d) 0.300 kg Silica bed at 120 Hz

6. Discussion

Summarizing the above, experimental values of captured dust for Potato Starch and Silica showed smaller difference between the two materials, than those produced by changing the vibration frequency. In order to properly account for the different materials properties and vibration conditions, the diffence at both the particle and bulk level should be considered.First of all, the volumetric average of the particle diameter, d_{pw}, and the density, ρ_p, allow to relate the dust release mass rate, w_d, with the dust particle number release rate, N_p. Assuming a particle spherical shape. Therefore, it is:

$$w_d = N_p \rho_p \pi d_{pw}^3 / 6 \tag{4}$$

Both materials tend to produce aggregates of different sizes depending upon the different bulk solids properties and upon acceleration. We assume that the number of released dust particles are proportional to the available aggregate surface area, A_t, and to the number of particles present per unit surface:

$$N_p \propto A_t / d_{pw}^2 \tag{5}$$

The available aggregate area, can be calculated from the bed volume:

$$A_t = \left\{ \left[H_b \frac{\pi D_c^2}{4} (1 - \varepsilon_e) \right] \Big/ \frac{\pi d_a^3}{6} \right\} \pi d_a^2 = H_b \frac{\pi D_c^2}{4} (1 - \varepsilon_e) \frac{6}{d_a} \tag{6}$$

where H_b and D_c are the bed height and column internal diameter respectively and ε_e is the voidage external to the aggregates. According to Barletta and Poletto (2012) it is possible to estimate this voidage from the

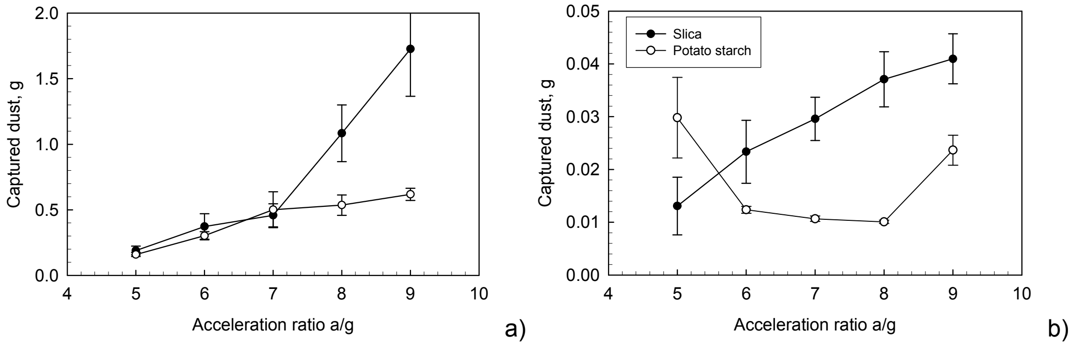

Figure 4: Captured dust at acceleration levels a/g between 5 and 9. Vibration frequency: a) 70 Hz and b) 120 Hz. Data points are the results of 10 repetitions. Error bars are standard deviations

aggregate density, ρ_a, and the average bed density, ρ_b. In turn, the aggregate density can be assumed to be equal to the bed density attained at the initial bed height, H_{b0},

$$\varepsilon_e = 1 - \rho_b / \rho_a = 1 - H_{b0} / H_b \tag{7}$$

We expect that the rate of the particle release is directly affected by the vibration movement and, in particular, to be proportional to the acceleration imparted to the superficial particles on the aggregates and to the frequency, f, that indicates how often this acceleration is imparted. On the other hand, we also expect that the release of dust particles is inversely proportional to the force, F_c, connecting a single particle to his neighbors:

$$N_p \propto fa\rho_p \frac{\pi d_{pw}^3}{6} \Big/ F_c \tag{8}$$

The connecting force, F_c, can be estimated by means of the Rumpf (1970) equation applied to the unconsolidated material characterized by a tensile strength, σ_{t0}:

$$F_c = \sigma_{t0} d_p^2 \varepsilon_i \big/ (1 - \varepsilon_i) \tag{9}$$

where d_p is the Sauter mean diameter and ε_i is the voidage internal to the aggregates, that coherently from the above hypotheses, can be estimated from the initial bed voidage. Combining Eqs (5) and (8):

$$\chi = N_p \Bigg/ \left(\frac{A_t fa\rho_p \pi d_{pw}}{6F_c} \right) \tag{10}$$

In particular, χ should be independent of the material and of the testing conditions. Table 2 reports the results of the calculations carried out to evaluate A_t, F_c, N_p and the ratio, χ of equation (10). Fc values calculated with Eq. (9) depend on bulk flow properties measured in independent experiments and are not an adjustable parameter. The derivation from bulk properties makes this evaluation inclusive of specific particle material properties such as shape or hardness. Results indicate that, in fact, χ values are rather independent of the acceleration for each tested material and that, furthermore, the proposed model correctly accounts for the different materials tested. In fact, limited differences occur between different materials at the same frequency, provided that we do not consider the results for Silica at a/g>7, where bubbling occurs. It is noteworthy that experiments at different frequencies show values of χ significantly different. It might be possible to interpret these results by considering not only the ability of the bed to release particles, but also the ability of the upper

Table 2: Model estimates

Material	f, s^{-1}	a/g	H_b, mm	H_{b0}, mm	w_d, μg s^{-1}	A_t, m^2	N_p, 10^5 s^{-1}	Fc, nN	χ 10^{-9}
Silica	70	5	60	48	6.3	7.92	4.92	3.5	287
		6	60	48	12.4	9.95	9.67	3.5	374
		7	60	48	15.3	11.26	11.88	3.5	348
		8	60	48	36.1	12.67	28.11	3.5	640*
		9	60	48	57.5	14.25	44.77	3.5	805*
	120	5	60	48	0.4	7.92	0.34	3.5	12
		6	60	48	0.8	9.95	0.61	3.5	14
		7	60	48	1.0	11.26	0.77	3.5	13
		8	60	48	1.2	12.67	0.96	3.5	13
		9	60	48	1.4	14.25	1.06	3.5	11
Potato Starch	70	5	55	45	5.3	3.02	0.67	10.6	374
		6	55	45	10.1	3.49	1.26	10.6	511
		7	55	45	16.7	3.99	2.09	10.6	635
		8	55	45	17.9	4.48	2.23	10.6	529
		9	55	45	20.6	4.98	2.57	10.6	488
	120	5	55	45	1.0	3.02	0.12	10.6	41
		6	55	45	0.4	3.49	0.05	10.6	12
		7	55	45	0.4	3.99	0.04	10.6	8
		8	55	45	0.3	4.48	0.04	10.6	6
		9	55	45	0.8	4.98	0.10	10.6	11

*Bubbling conditions.

layers of the bed to capture the dust released by the lower layers. It is likely, in fact, that frequency can affect this ability (Chirone and Urciuolo, 2009). Therefore, a better understanding of the observed results requires a better insight not only of the particle release, but also of the particle capture mechanisms.

7. Conclusions

An experimental procedure has been set up for the evaluation of the dust emission from vibrated powders. A theoretical approach has been developed to account for the effect of process conditions based on the estimates of the cohesive material aggregate size and on the effects of vibration on the dust release. This approach is able to catch most of the effect due to acceleration, and different material, but it is not able to correctly account for the effect of frequency. It is hypothesized that better insight of the problem might come from a deeper understanding of the dust recapture phenomena.

Acknowledgements

Authors are grateful to Ms Nicoletta Lotrecchiano for her constructive help with the experiments.

References

Barletta D., Donsì G., Ferrari G., Poletto M., Russo P., 2007, Solid flow rate prediction in silo discharge of aerated cohesive powders, AIChE Journal, 53, 2240-2253. DOI:10.1002/aic.11212

Barletta D., Donsì G., Ferrari G., Poletto M., Russo P., 2007, The effect of mechanical vibration on gas fluidization of a fine aeratable powder, Chem. Eng. Res. Des., 86, 359-369 DOI:10.1016/j.cherd.2007.10.002

Barletta D., Poletto M., 2012, Aggregation in fluidization of cohesive powders assisted by mechanical vibrations, Powder Technol. 225, 93-100, DOI:10.1016/j.powtec.2012.03.038

Chirone R., Urciuolo M., 2009 Role of bed height and amount of dust on the efficiency of sound-assisted fluidized bed filter/afterburner, AIChE Journal, 55 (12), 3066-3075. DOI: 10.1002/aic.11951.

Faschingleitner J., Höflinger W., 2011, Evaluation of primary and secondary fugitive dust suppression methods using enclosed water spraying systems at bulk solids handling, Adv. Powder Technol., 22,236-244. DOI: 10.1016/j.apt.2010.12.013

Geldart D., 1973, Types of gas fluidization, Powder Technol., 7, 285-292. DOI:10.1016/0032-5910(73)80037-3

Grima-Olmedo C., Ramírez-Gómez A., Medic-Pejic L., García-Torrent J., 2014, The penetration of respiratory protective devices by respirable solid particles. J. Aerosol Sci., 74, 36-41. DOI:10.1016/j.jaerosci.2014.03.008

Hamelmann F., E. Schmidt E., 2004, Methods for characterizing the dustiness estimation of powders, Chem. Eng. Technol., 27, 844–847, DOI: 10.1002/ceat.200403210.

Rumpf H., 1970, On the theory of the tensile strength of agglomerates in force transmission at contact points (Zur Theorie der Zugfestigkeit von Agglomeraten bei der Kraftübertragung an Kontaktpunkten), Chemie Ingenieur Technik, 42, 538-540. DOI: 10.1002/cite.330420806.

Saleh K., Moufarej Abou Jaoude M. T., M. Morgeneyer M., E. Lefrancois E., O. Le Bihan O., J. Bouillard J., 2014, Dust generation from powders: A characterization based on stirred fluidization, Powder Technol. 255, 141-148, DOI:10.1016/j.powtec.2013.10.051.

Schulze D., 1994, A new ring shear tester for flowability and time consolidation measurements, Proc. 1st Int. Particle Technology Forum, August 17-19, Denver, USA, 11–16.

Tomasetta I., Barletta D., Poletto M., 2011, The effect of temperature on flow properties of fine powders, Chemical Engineering Transactions, 24, 655-660. DOI: 10.3303/CET1124110.

Tomasetta I., Barletta D., Poletto M., 2013, The High Temperature Annular Shear Cell: A modified ring shear tester to measure the flow properties of powders at high temperature, Advanced Powder Technol. 24, 609–617. DOI: 10.1016/j.apt.2012.11.007

Wypych P., Cook D., Cooper P., 2005, Controlling dust emissions and explosion hazards in powder handling plants. Chemical Engineering and Processing: Process Intensification, 44(2), 323-326. DOI: 10.1016/j.cep.2004.02.026.