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Dust generation from powders: A characterization test based on stirred fluidization

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ABSTRACT

The aim of this paper was to develop an experimental test based on combination of fluidization and stirring in the perspective of its use for dustiness assessment. A parametric study on various factors that influence the release of fine particles (considered as dust) from a fluidized bed of binary mixtures of coarse and fine particles is presented. The emission of fine particles is found to be lower when the density of fine particles is high, and when the fluidization gas velocity, the mean size and the relative amount of fine particles in the mixture are low. Different binary mixtures with various fine/coarse fractions were tested in a classical fluidized bed as well as in a stirred fluidized bed. The experiments show that the total recovery of fine particles obtained by the combined test exceeds 80% whereas for the same aeration conditions and test duration, the classical fluidized bed releases only about 20% of the total mass.

1. Introduction

A large majority of raw materials as well as intermediate or final products used in the chemical industry are constituted of powders [11,31]. This is due to the advantages that powders provide compared to liquids, *e.g.* transport facility, storage and volume reduction. Consequently, processes using or producing powders are encountered in all sectors: the food industry, pharmacy, metallurgy, chemistry and the mineral industry. However, the use of powders has also major drawbacks such as dust emission, leading to several risks related to economics, health, hygiene, product quality and process safety. For example, in process steps, such as transport, fluidization, drying processes and bulk packing, a part of the handled powder can be dispersed into the working environment. To improve the management of these risks or occupational health, quantifying dustiness is very important and it is essential to develop simple, fast and reliable tests to characterize the propensity of a powder to emit dust.

Dust in a powder comes in the forms of releasable, freely moving particles, agglomerates of fines and fines attached to larger particles. The last two categories will release the dust in the form of fine particles by single or coupled mechanisms, for example, shearing, attrition and collision, followed by transfer or disintegration. According to labor legislation, a *dust* is defined as a particle with an aerodynamic mean diameter less than 100 μm and a terminal settling velocity lower than 0.25 m s^{-1}. However, in practice, this definition needs to be qualified and the term dust refers to fine particles in general (*i.e.* d_p < 100 μm). In this paper, the latter description is used. Furthermore, *dustiness* refers to the propensity of a powder to release fine and suspendable particles. Generally, the dustiness of a powder depends not only on the particle properties but also on external constraints exerted by the process. Therefore, it may be difficult to exactly assess the amount of dust a powder can release by a single test. Indeed, several particle detachment mechanisms, such as shear, impact, attrition and collision need to be taken into account. Furthermore, no universal and rigorous approach exists to adapt the real constraints a powder undergoes during its handling to a laboratory setting. This also explains the variety of available dustiness testing methods whose common procedure involves the following steps [19]:

— taking a representative sample of the powder,
— applying constraints to the sample,
— releasing the dust,
— sampling the emitted dust,
— analyzing the emitted dust.

The first three steps can be continuous, discontinuous or intermittent. The choice depends on the nature of the sample, the amount of dust released and the properties of the dust fraction. Three major dust tests have been reported in literature: the drop test, in a column or in a box (such as a room) (*e.g.* [3,14,29,34]), the fluidization test (*e.g.* [1,39]), and the rotating drum test (introducing mechanical dispersion or agitation constraints) [10,20,33]. In addition, in order to get closer to the process constraints, a test combining the column drop

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test and the rotating drum test has also been reported (*e.g.* by [38]). However, these tests are limited to specific situations or have only comparative significance. This is mainly due to the difficulty to adapt the solicitations a powder undergoes in a given process to another one (*e.g.* to make a correspondence between shear conditions in a fluidized bed and a rotary drum). Therefore, there is still a need to develop new tests for proper assessment of dust emission. Ideally, a suitable test should be able:

— to cover a wide range of stresses encountered in practical situations and various processes. This condition is necessary for the extension of the test to a larger variety of industrial situations.
— to determine the intrinsic amount of dust contained in a powder (*i.e.* the maximum amount of dust which can be released hypothetically).

Then, the combination of these two requirements allows reliable estimation of dust emission under real process conditions. In addition, the test should be amenable to a theoretical description allowing for a rational interpretation of results. The present study focuses only on the second requirement.

Taking into account these requirements, a test based on solid/gas fluidization seems particularly interesting from several points of view:

— first of all, a number of powder handling and processing operations make use of fluidization because of high heat and mass transfer rates achievable by this technology. The data from the dustiness test could be directly used for these operations;
— this technique possesses a high flexibility and is able to cover both low and high shear conditions (*i.e.* from aerated fixed beds to turbulent fluidized beds). Moreover, additional shear stresses could be brought by stirring and/or vibration.
— substantial literature on the elementary mechanisms involved in the removal of fine particles from fluidized beds is available. This phenomenon known commonly as *elutriation* could be advantageously used to characterize the dust emission.

In the present work, a dustiness test based on the combination of fluidization and stirring is investigated. This simple and practical test takes advantage of elutriation and entrainment phenomena taking place during fluidization. These phenomena are amplified by the stirring of the powder using a rotating blade with a helical path.

1.1. Fine removal from fluidized beds

In a fluidized bed, the gas leaving the system carries some suspended particles. The mass flux of the suspended solids in a given height is known as *entrainment* or *carryover* [16,24]. Although in the freeboard section the suspension contains initially the whole spectrum of particle sizes, the proportion of fine particles increases with the disengaging height because the larger particles fall back to the bed. In fluidization technology, the term *elutriation* refers to the process in which fine particles are separated from a mixture and carried out of a fluidized bed due to the fluid flow rate passing through the bed (*e.g.* [24]; Davison and Harisson, 1971; [44]). Typically, elutriation occurs when the superficial velocity through the bed exceeds the terminal velocity of the fines in the bed. However, elutriation can also occur at lower velocities.

Note that the dust in a powder comes in many forms: free flowing fine particles easily suspended [30], fine particles agglomerated together and/or attached to coarser particles [6,18,21,22]. The last two categories are harder to aerosolize because of the forces of cohesion and adhesion between particles. Geldart and Wong [18] and Yadav et al. [45] showed this influence on aerosolization. Fine particles are suspended after single or coupled mechanisms, such as shearing [46], attrition (abrasion or fragmentation) [13,25], or collisions (followed by transfer of dust between the powder particles or by the disintegration of agglomerated dust) [5,35]. Liu and Kimura [28] showed that fine particles which are agglomerated or attached to coarser particles could detach due to the phenomenon of attrition and are gradually entrained by the fluidizing air. Arena et al. [4] and Chirone et al. [12] observed that the fine particles generated by attrition in a bimodal powder mixture control the elutriation. Ayazi Shamlou et al. [5] indicated that the attrition may occur purely by the effect of hydrodynamics in the bed and depends on the fluidizing air velocity, the particle size and the remaining agglomerated dust fraction. This demonstrates that the generation of fines is not independent of the mass in the bed and suggests a non-linear increase in the mass of elutriated fines with time. Based on these different explanations, we can make the following assumptions in describing the elutriation phenomenon during fluidization:

- fine particles in the bed are in three different forms, either free or attached to the powder or agglomerated together.
- attrition is a phenomenon allowing the dispersion of attached (to a surface) or agglomerated fine particles. In our case, attrition is used to define the phenomenon of detachment of fine particles adhered to the powder or agglomerated together.
- generation of fines through attrition is a non-linear function over time and depends on the fluidizing air velocity applied, the size of the dust particles and the fraction of agglomerate dust remaining in the bed.
- dust generation by attrition of larger particles is negligible.

1.2. Agitated fluidization

Previous studies have shown that stirring improves the state of the fluidization of mixtures but facilitates the elutriation of fine particles. The stresses applied by the friction of the stirrer blades with the agglomerates and large particles, as well as the extra energy communicated to the particles by stirring, de-agglomerate the aggregate and detach dust particles. The inter-particle forces increase as the particle size decreases (*e.g.* [40]), making, in most cases, the fluidization difficult or impossible. The further supply of mechanical energy can assist the fluidization of cohesive powders. Kozulin and Kulyamin [23] showed that, in a fluidized bed, the agitation of the powder reduces slugging and the appearance of preferential passages. For particles belonging to Group B of Geldart's classification, this phenomenon is accompanied by a decrease in pressure drop and the minimum fluidization velocity of the particles [7]. The reduction in pressure drop is of the order of 25% and it is due to the extra energy transmitted to the particles, through the agitation, leading to a good aeration. Concerning the very fine particles, Brekken et al. [8] observed that powders such as flour and starch (belonging to Group C of Geldart's classification, *i.e.*, cohesive particles which are not, or are difficultly, fluidizable) can be fluidized in the presence of aeration and agitation. Moreover, they proved that a mixture is best fluidized when the fluid velocity and agitation are increased [9]. When comparing different tests at decreasing fluidizing velocities, Nezzal and Guigon [32] noted that the behavior in a conventional fluidization and in agitated fluidization varies with the powder and inter-particle forces of cohesion. Three types of behavior were identified:

— for Group B powders (easy to fluidize powders), the agitation has no influence on the fluidization behavior
— for Group A (aerable, fluidizable) powders, agitation decreases the minimum fluidization velocity and highlights the role of cohesion in the de-aeration
— for Group C powders, whose natural fluidization is very difficult if not impossible, agitation would permit the fluidization.

In addition, the stirring speed did not have the same influence on all powders. For some particles, fluidization is improved by increasing the rotational velocity. For others, generally very cohesive powders for which the required velocity is too high, the fluidization can become difficult. For high stirring speeds, the centrifugal forces push the particles against the wall and a central chimney is formed. This behavior depends largely on the friction coefficient of the particles that characterizes the