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From Dust Dispersion to Dust Explosion

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The performances of four dispersion nozzles were studied: the standardized rebound nozzle and the mushroom-cup, and two additional nozzles called mushroom nozzles having different surface section area for air injection. Their influences on the in-situ particle size distribution (PSD) and their impact on the explosion severity were assessed. Discrepancies depend on the powder nature and initial PSD, but also on the injection dynamics. Fragmentation effects were highlighted with the rebound nozzle and a mushroom nozzle (type A), which improves the explosion severity. On the contrary, dust lifting is sometimes not sufficient with the mushroom-cup, which is perceptible focusing on the overpressure evolution. If the rebound nozzle is conservative in most cases, its use should not be systematic and alternative designs, as mushroom nozzles, can sometimes be preferred.

* 1. Introduction

While standardization is necessary, uniformity is not. For example, the use of a single experimental protocol to determine the explosivity characteristics of powders, as set out in ISO 80079-20-2 (2016), does not always consider the materials specificities (density, shape, polydispersity, sensitivity to friction...) and the wide range of industrial conditions. So, within the framework of standardised protocols, it can be useful to adapt the test equipment to industrial constraints. Fortunately, alternatives exist – standardized or not - and are constantly being developed.

Although not exhaustive, the following cases illustrate situations where standard experimental protocols can lead to some issues: i) the dispersion of explosive or pyrophoric powders (nitrocellulose, metal nanopowders…) using the pressurised container at 20 bar and through the inlet-valve might cause their pre-ignition (Santandrea et al., 2020), ii) the dispersion of long fibres or sticky materials using the same set-up can increase their agglomeration and reduce their dispersibility (Iarossi et al., 2015), iii) brittle or temperature-sensitive powders can be modified by their injection under high pressure and by the significant temperature change caused by gas expansion in the sphere, iv) oleaginous products or solvent-containing powders which can release liquids when pressurised. In the above cases, in-situ powder dispersion in the sphere may be more advantageous and more in line with actual industrial conditions than injection at 20 bar. Another application is related to secondary explosion after lifting of a dust layer. By using in-situ dispersion, the differential resuspension of powders of different sizes, densities and shapes can be studied.

The nozzle used in the 20L sphere tests is a key part of the experimental set-up, influencing cloud homogeneity/uniformity, turbulence and particle size distribution. Three kinds of nozzles, the perforated annular nozzle, rebound nozzle and mushroom cup, can already be used for standardized tests, the latter being preferred “if it is not possible to adequately disperse the material with the rebound nozzle” as stated by ISO 80079-20-2 (2016). In addition to these nozzles, several alternatives have already been proposed and tested both in the 20L and 1m3 vessels (Dahoe et al., 2001; Huéscar Medina et al., 2015; Pinilla et al., 2019; Spitzer et al., 2024).

This work aims at comparing the performances of four nozzles: the standardized rebound nozzle and mushroom-cup (ISO, 2016) and two mushroom nozzles recently proposed by the University of Pardubice and the Technical Institute of Fire Protection (Spitzer et al., 2024). Their influences on the in-situ particle size distribution (PSD) and the dust cloud turbulence were analyzed, as well as their impact on the explosion severity.

* 1. Materials and methods

Both dispersion and explosion tests were performed in a 20L explosion sphere according to the EN 14034 series (CEN, 2011). The ignition delay time was set at 60 ms.

* + 1. Powders

Four powders were chosen: lycopodium, due to the monomodal nature of its particle size distribution (PSD), wheat starch and cellulose, due to their industrial applications and niacin, or vitamin B3, as it is used as calibration powder for the explosion sphere. The ex-situ PSD shown in Table 1 was determined using a laser sensor equipped with a dry dispersion unit (Malvern Mastersizer 3000 – Aero S). Lycopodium, starch and niacin can be considered as fine powders, having characteristic diameters lower than 100 µm; however, the cohesive, moisture-sensitive nature of starch must be emphasized. Cellulose (Vivapur 200) contains long fibrous particles which tends to entangle during their dispersion.

Table 1: Characteristic diameters of the particle size distributions

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| --- | --- | --- | --- |
| Particle size (µm) | d10 | d50 | d90 |
| Lycopodium | 26 | 31 | 37 |
| Wheat starch | 27 | 62 | 81 |
| Niacin | 7 | 27 | 77 |
| Cellulose | 65 | 219 | 463 |

* + 1. Nozzles and dispersion system

The sphere was vacuumed down to 400 bar ± 5 mbar before each test. The injection pressure was set at 20 barg in order to keep the pre-ignition pressure rise (PIPR) as close to 0.6 as possible (Spitzer et al., 2024). Some pressure adjustments are required during tests depending on the powder concentration. Four nozzles were tested (Figure 1), two of which are already standardized: the rebound nozzle (injection through the inlet valve - 1a) and the mushroom-cup (dust lifting - 1b). Two additional nozzles were proposed, directly based on the design of the mushroom-cup, but without the cup (Figure 1c, d). The only difference between both mushroom-nozzles ‘A’ and ‘B’ is the cross-section area used to inject the gas: 157 mm² and 207 mm², respectively (Figure 1e and f). Preliminary tests were already performed with mushroom nozzle A (Spitzer et al., 2024). As with the mushroom-cup, dust is deposited around the mushroom nozzles before vacuuming and air injection.

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*Figure 1: Picture of the three types of nozzles used for dispersing the powder in the 20L sphere*

* + 1. Particle size distribution measurements

A 20L sphere equipped with five windows was used to determine the PSD during the powder injection, which highlights potential fragmentation phenomena and stresses the differences with the initial PSD. Measurements were carried out in-situ with a laser diffraction sensor (Helos - Sympatec) with a maximum frequency of 2000 Hz, Two different lenses were chosen as a function of the initial PSD of the samples (Table 1): R3 for PSD ranging from 0.5 to 175 µm and R5 from 0.5 to 875 µm (31 segments detector).

* 1. Results and discussion

Explosions tests were performed for each powder at concentrations close to maxima, or over wider ranges. Repeatability trials were done for each maximum.

* + 1. Influence of nozzle design on explosion severity

Figure 2 shows that the explosion overpressures obtained with the rebound nozzle and the mushroom nozzle type A are similar. pmax obtained with the type B mushroom nozzle is consistent with that of rebound and type A nozzles, although there is a slight shift in concentration. However, a significant difference is obtained by using the mushroom-cup, leading to a lower maximum overpressure pmax by 10 %. The trends observed for the maximum rates of pressure rises are of the same order, but with even more marked tendencies. The type B mushroom nozzle and the mushroom-cup yield to lower dp/dtm values. It is worth noting that the more conservative results were not obtained with the rebound nozzle but with the mushroom nozzle type A (Figure 1c). The maximum rate of pressure rises (dp/dt)max are reached at higher concentrations for the mushroom-cup and for the mushroom nozzle B, respectively at 750 and 1250 g.m-3 (500 g.m-3 for the two other nozzles).

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*Figure 2: Effect of the nozzle design on maximum overpressure (left) and maximum rate of pressure rise (right) of lycopodium*

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*Figure 3: Effect of the nozzle design on pm (left) and dp/dtm (right) of wheat starch*

For starch, the maximum explosion severities are also obtained with the rebound nozzle and the mushroom nozzle - type A (Figure 3). While variations in maximum overpressure between nozzles are significant (up to 18 %), the differences are even more significant in terms of explosion kinetics, i.e. (dp/dt)m. The shift towards higher concentrations and differences in maxima suggest that both the amount of powder dispersed and the turbulence of the dust cloud might be reduced when using the mushroom-cup or the mushroom nozzle - type B. These variations are probably more pronounced here, due to the highly cohesive nature of starch.

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*Figure 4: Effect of nozzle design on the maximum overpressure (left) and maximum rate of pressure rise (right) of cellulose*

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*Figure 5: Effect of nozzle design on pm (left) and dp/dtm (right) of niacin*

Figures 4 and 5 confirm the previous trends. Although the maxima obtained are within acceptable orders of magnitude for all the nozzles used (Spitzer et al., 2023), they are not necessarily obtained at the same dust concentrations. During explosion tests performed with the mushroom-cup, especially for lycopodium and niacin, small amounts of unburned powder were collected under the cup after testing, which may explain why a higher concentration has to be injected to obtain the same optimum (Figure 5). For the majority of powders tested, conservative values were obtained for the rebound nozzle. Although it offers a larger air ejection surface, the explosion severity measured with the type B mushroom nozzle is frequently lower to that of other configurations. Considering that the same amount of powder is dispersed, which is confirmed by a pmax comparable to other nozzles, lower dp/dtm values are probably due to a lower gas velocity and therefore to a reduced turbulence. The even positioning of the powder around the nozzles prior to testing is also a critical point to master.

* + 1. Influence of nozzle design on particle size distribution

In-situ dispersion tests were carried out with the four powders and nozzles. Figures 6 and 7 show the PSD determined at 60 ms ± 5 ms.

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Figure 6: Influence of the nozzle design on the PSD of lycopodium and starch inside the 20L sphere

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Figure 7: Influence of the nozzle design on the PSD of niacin and cellulose inside the 20L sphere

Figure 6a shows that, as expected, the PSD of lycopodium does not change much as a function of the nozzle. A small fragmentation phenomenon is yet visible around 10 µm for the rebound nozzle, which is consistent with the high shear stresses developed by this dispersion system (Kalejaiye et al., 2010). Thus, the variations in explosion severity observed in Figure 2 cannot be explained by a change in PSD. The assumption of less efficient dispersion in the case of the mushroom-cup and, less notably, the type B mushroom nozzle is therefore supported. Figures 6b and 7b demonstrate that both rebound nozzle and mushroom nozzle type A lead to finer particles, which will increase the reactive surface of the powders and promotes their explosion severity, especially their combustion kinetics, as confirmed by the results displayed in Figures 2 to 5. The hypothesis of partial entrainment of the powders (lifting of the finest dust, mainly) must be evoked, as it could explain why, with potentially less intense shear stress, Janovsky’s nozzle type A leads to PSD sometimes finer as those observed with the rebound nozzle. However, a validation of this assumption would coincide with lower explosion overpressures in the case of the mushroom nozzle type A, which does not appear to be the case in view of the results described in the previous section (Figures 2 to 5, left). The greatest differences in PSD were measured for cellulose (Figure 7), which is consistent with the fact that this is the material with the widest PSD, but also a shape conducive to less homogeneous dispersion and more interactions between particles, e.g. entanglement of the fibers. As for niacin (Figure 7a), it is worth noting that a small deviation of the PSD towards large diameters is observed for the cellulose (Figure 7b). However, this phenomenon is not observed between 30 and 50 ms, nor after 70 ms, bearing in mind that PSD evolves significantly during dispersion. Finally, the difference in cross-section area between the two mushroom nozzles plays a role in dust lifting and, most probably, in the turbulence generated in the 20L vessel. Particle Image Velocimetry tests are underway to examine this assertion.

* 1. Conclusions

Explosion tests carried out with different nozzles have demonstrated the importance of this element on the maximum rate of pressure rise (the maximum overpressure being less affected) and on the particle size distribution in the vessel. If the most conservative results are often obtained with the rebound nozzle, it is sometimes not advisable to introduce the powder sample in the dust container, e.g. in the case of coarse powders, flocky dusts and friction-sensitive or pyrophoric materials. In such situations, the mushroom nozzle - type A has proved to be an interesting alternative. If it sometimes leads to less effective dispersion, the use of the standardised mushroom-cup reduces the fragmentation phenomenon observed with the rebound nozzle. This has the advantage of avoiding the powder breakage that alters its reactive surface.

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