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Proposal of a new injection nozzle to improve the experimental reproducibility of dust explosion tests

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ABSTRACT

The influence of the injection nozzle on the dispersion process of a combustible dust in the 20 L sphere is established by developing a descriptive analysis. This study compared the evolution of a dust cloud formed thanks to the standard rebound nozzle with that formed from a new symmetric nozzle. For this purpose, a CFD simulation based on a Euler-Lagrange approach characterized the physical properties of the dust-air mixture in the explosion chamber. The computational results established that the symmetric device enhanced the homogeneity of the mixture as well as the initial turbulence during the initial stage of dispersion. Nevertheless, it also constituted a more rapid turbulence decay due to a wider expansion of the gas. Thus, it constituted different sedimentation and agglomeration periods with regard to the standard device. Thereupon, the computational tools determined the most appropriate ignition delay for the dust cloud for each injection nozzle.

1. Introduction

The comprehension of the major hazards that can be associated with the formation of a combustible dust cloud is based on the proper characterization of the powder explosibility parameters in a confined environment. This analysis can be constituted by performing a set of laboratory tests that establish the explosion characteristics of the cloud according to specific standard test methods. One of these particular tests, and probably the most common one, is carried out with the 20 L apparatus that was developed by Siwek [1]. The operating procedure of this experimental setup is described in detail in various international standards. For instance, the American Society for Testing and Materials presents the main specifications of the 20 L apparatus as well as the corresponding protocol in the standard ASTM E1226-12a. Similar information is provided by the German Society of Engineers (VDI-3673) and the International Standards Organization (ISO 6184/1).

The experimental setup of the standard test consists of a 20 L spherical explosion chamber connected to a pressurized canister by a solenoid valve. The sphere is surrounded by a cooling jacket with water at controlled temperature. The canister will form a confined dust cloud by injecting a two-phase flow into the sphere through a dispersion nozzle installed at its bottom. Thereafter, the dust-gas mixture is ignited after a delay, also called t_v, that is specified prior to the development of the test. In accordance with this protocol, the ignition of the cloud is preceded by the following steps:

1. The dust sample is weighed and loaded in the canister and chemical ignitors are placed in the center of the sphere. The standard ignition energy is 10 kJ (corresponding to two 5 kJ chemical ignitors) for the determination of the explosivity parameters and 2 kJ (two 1 kJ ignitors) for the minimum explosive concentration (MEC) determination.
2. The dispersion chamber is evacuated to 0.4 bar, whereas the canister is pressurized up to 21 bar(a).
3. The solenoid valve is opened and the two-phase flow forms the cloud.

The third step of this protocol determines the main characteristics of the dust/gas mixture before its ignition. The dust cloud formed inside the 20 L sphere defines a transient behavior that is constituted by the fluidization of the solid sample, which induces continuous variations of the physical properties of the gas and the dispersed powder. Therefore, it will also define the propagation of the combustion flame that develops within the 20 L sphere [2]. Consequently, these changes affect the ignitability of the cloud and the violence of the explosion [3,4]. For this reason, the description of the evolution of the confined dust cloud has been considered as an aspect of major concern for the definition

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of the most conservative conditions to perform an explosibility test with the 20 L apparatus.

The changes occurring in both phases during the pre-ignition stage are directly associated with the initial or 'cold' turbulence that is generated by the injection of the high-pressure two-phase flow [5,6]. The "cold turbulence" being related to the parameter t_v, the most appropriate ignition delay can be determined by studying the behavior of the dust-air mixture and the variables that are linked to its turbulence levels. Previously, some anemometry measurements were performed by Dahoe et al. in order to establish how the turbulence of the gas flow varied during the pre-ignition stage [7]. In addition, some similar analyses were reported by Pu et al. [8]. Moreover, Kalejaiye et al. developed an analysis of the solids distribution inside the explosion chamber that was based on light transmittance [9]. This study concluded that the variations of the particle size distribution of the combustible dust affected the assessment of its local concentration and that the dispersion process does not constitute a completely homogeneous dust cloud with the two injection nozzles that are commonly used in the 20 L sphere (rebound and perforated annular nozzles). This heterogeneity can have a strong influence on the experimental reproducibility, which is rather low notably with regard to the determination of the maximum rate of pressure rise. The relative standard deviation of repeatability on this parameter is generally estimated at $\pm$ 10 to 15%.

In addition, various comparative tests have analyzed experimentally the influence of the shape of the injection nozzle on the development of the confined cloud. For instance, Dahoe et al. established that the size and conditions of the jets formed by the dispersion nozzle influence the initial turbulence decay rate [5]. This fact defines the influence of the injection nozzle on the evolution of the dust cloud during the pre-ignition stage. For this reason, Sanchirico et al. performed granulometric analyses on dust samples of different solid materials before and after dispersion in the 20 L sphere. They demonstrated that the particle size distribution (PSD) of the dust collected after the dispersion process was greater with the utilization of the standard rebound nozzle with regard to the standard perforated ring [10]. In the same manner, Mercer et al. determined experimentally the variations of the velocity field of the gas flow that are defined by the geometry of the injection nozzle and the instant of the dispersion process [11]. Moreover, Krietsch et al. developed a special mushroom nozzle in order to improve the dispersion of metallic nanometric powders [12]. The samples were placed inside the explosion chamber before the dispersion process and not inside the pressurized canister. In the same manner, Zhang and Zhang analyzed the influence of the ignition delay on the explosibility parameters of corn/air mixtures with a nozzle composed of several holes at the surface [13]. This device intended to create a group of jets that are directed towards many regions of the vessel. These studies agree by concluding that the shape of the injection system constitutes an adaptable parameter to perform an explosibility test with the 20 L sphere.

Then, it appears that the development of a new dispersion nozzle can be an efficient and simple solution to improve the homogeneity of the dust cloud and, as a consequence, to increase the experimental reproducibility. In addition, previous studies have demonstrated that the computational analyses become a useful tool to describe the dust dispersion within the explosion chamber. Then, the results obtained can contribute to a better comprehension of the interaction mechanisms of each solid particle with its surrounding particles and the internal walls that occur during the pre-ignition test [14,15]. At first, a new dispersion nozzle was designed, tested and the results were compared with those obtained by using a standard rebound nozzle. In parallel, the evolution of the dust-air mixture obtained with two different injection nozzles was described with a set of CFD simulations. These computational tools constitute a widely adopted methodology to characterize the phenomena associated with explosive dust clouds [16,17]. For this purpose, the computational approach has been associated with a Discrete Element Method (DEM) to represent accurately the gas-solid fluidization characteristics of the combustible dust cloud [18]. Finally, the numerical results were compared to the previous set of experimental tests.

2. Materials and methods

2.1. The 20 L dispersion sphere

The descriptive study of the behavior of a combustible dust cloud in the 20 L sphere is hard to accomplish due to the absence of a visualization window with a sufficiently large diameter. For this reason, a whole new dispersion vessel was constructed in order to obtain a visualization field from different views.

The apparatus shown in Fig. 1 was built with stainless steel and was installed on the outlet valve of the experimental setup in order to replace the original chamber. Some modifications were included in the design of this vessel to make it suitable for a dispersion analysis. For this purpose, five windows have been placed in the structure of the chamber to provide several points for the visualization of the dust cloud: four circular windows located at the lateral extremes of the apparatus and another one at the top. On the one hand, the lateral windows are made of borosilicate with a diameter of 9.7 cm and are sustained by flanges. They were utilized for the data acquisition through in situ granulometric analyses (Helos Vario - Sympatec GmbH) and Particle Image Velocimetry (PIV) measurements. On the other hand, the window that is located at the top of the vessel is made of polymethyl methacrylate and has a diameter of 14 cm. This window was used for the recording of the dispersion process with a PhantomV91 high-speed video-camera and for cleaning purposes. It should be added that, if this new vessel can withstand the pressure variation due to the dust dispersion, it was not designed to withstand explosion overpressures. This experimental setup was considered for the descriptive tests according to the following procedures:

i) Particle Image Velocimetry: The high-speed camera was placed in front of one of the four lateral windows and was adjusted to visualize the geometric center of the sphere. The recordings were obtained for an interrogation window of 2.95 cm $\times$ 2.80 cm with an image resolution of 480 $\times$ 480 pixels and a framerate of 6410 fps. The analysis envisaged the description of the velocity field with two different positions of the standard rebound nozzle: parallel and perpendicular to a continuous laser sheet that illuminated the interrogation window. Subsequently, 0.6 g of micrometric wheat starch were charged into the storage canister of the standard apparatus in order to obtain a nominal dust concentration equal to 30 g/m^3. A dispersion test was carried out according to the specifications of the standard procedures. This fact allowed describing the evolution of the velocity field during the first 120 ms when no ignition occurs. For this purpose, a set of five replicate tests was performed for each configuration of the injection nozzle.
ii) Granulometric analyses: The same weight that was considered for the PIV analyses was determined for the wheat starch samples used in these tests. Another dispersion test established the evolution of the particle size distribution during the 120 ms elapsed after the arrival of the bulk of the dust cloud to the geometric center of the sphere, in which a laser beam is positioned. For this purpose, the granulometric data were registered in measurement cycles of 1 ms and reported for intervals of 5 ms. A set of five replicate tests was performed for the granulometric analysis in order to verify the repeatability of the tendencies evidenced in the experimental results.

2.2. Design of a new nozzle

The scheme of the standard rebound nozzle is shown in Fig. 2. A The geometry of this nozzle clearly implies that two main directions will be