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Combining CFD simulations and PIV Measurements to Optimize the Conditions for Dust Explosion Tests

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Two studies were developed in parallel on the dust dispersion in a tube during a flammability test. On the one hand, an experimental set-up composed of a Particle Image Velocimetry (PIV) system, a high speed video camera and a laser diffraction sensor was used to characterize the dust cloud, notably the mean velocity of the particles, the root-mean-square velocity and the turbulence intensity. On the other hand, a Computational Fluid Dynamics (CFD) simulation was developed by using an Euler-Lagrange approach.

Good agreements were obtained between particle velocities and turbulence levels measured by Particle Image Velocimetry and those determined by simulations. The relation between the initial turbulence and the homogeneity of the dust dispersion has also been discussed.

Three stages have been identified during the dust dispersion: a first phase of turbulence intensity increase due to the presence of powerful air jets, a second phase of the turbulence decrease during which the velocity vectors are less oriented and the dust cloud tends to be more uniform and a third represented by the particles settling. The relevance of the electrode positioning as well as the choice of the ignition delay tv in order to perform reproducible flammability tests have also been discussed.

In the short term, these results will improve our predictive models on dusts explosions. In the medium term, this study will advocate modifications of the existing procedures/standards in order to define, ab initio, the suspension characteristics which will better correspond to actual industrial conditions or, which will lead to the worst case scenario.

1. Introduction

The ignition and explosion parameters of combustible dusts are determined on the basis of international standards that set the tests conditions (IEC, 1994). However, it is usual to notice that applying such conditions do not systematically lead to the safest parameters. For instance, the ignition delay time, which is the delay between the dust dispersion into the test vessels and its ignition (60 ms for the explosion sphere, for instance), is inadequate for most of the powders and even more for nanoparticles. The flame propagation being linked to the suspension aerodynamics (Garcia-Agreda et al., 2010; Zhen and Leukel, 1996), a better knowledge of the initial suspension characteristics will enable an informed choice of the tests conditions (IEC, 1994).

The aim of this work is to study the particles suspension in a turbulent flow, which characteristics match those encountered in our standardized equipments (explosion tube, 20L sphere). In this article, only the dust dispersion in a modified Hartmann tube is discussed. This research was carried out according to two complementary approaches. On one hand, the experimental part of this study was aimed at identifying the main parameters affecting the particles suspension. On the other hand, Computational Fluid Dynamics (CFD - Ansys Fluent) was used to represent the dust cloud aerodynamics.

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2. Materials and methods

Tests have been carried out on explosion tubes equipped with the same dispersion nozzles, which correspond to the one used in the Hartmann tube (Di Benedetto et al., 2011). The first experiments were carried out with non cohesive powders (glass beads) in order to validate the method. Further tests were performed on wheat starch powders under controlled temperature and humidity conditions.

2.1 Experimental set-up for Particle Image Velocimetry (PIV) experiments

In order to quantify the turbulence generated by the dispersion of a dust cloud by an air flow inside a vertical tube a Particle Image Velocimetry system (PIV) was implemented. In this purpose a square tube of tempered borosilicate of 7x7x40 cm dimensions was used to visualize the dust dispersion obtained by a Mike 3 apparatus (Kühner AG). The experimental set-up was composed of a PIV system (in black on figure 1) and a high speed video camera (Phantom V9.1) at 1000 to 4000 fps in this study.

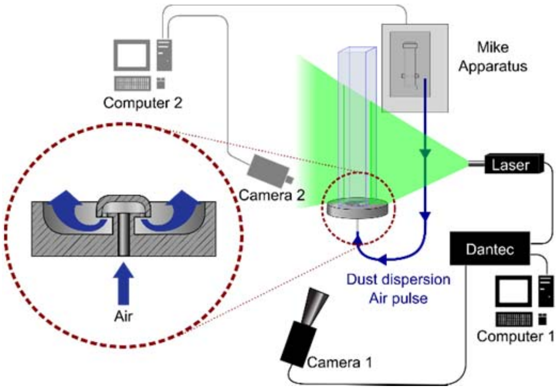
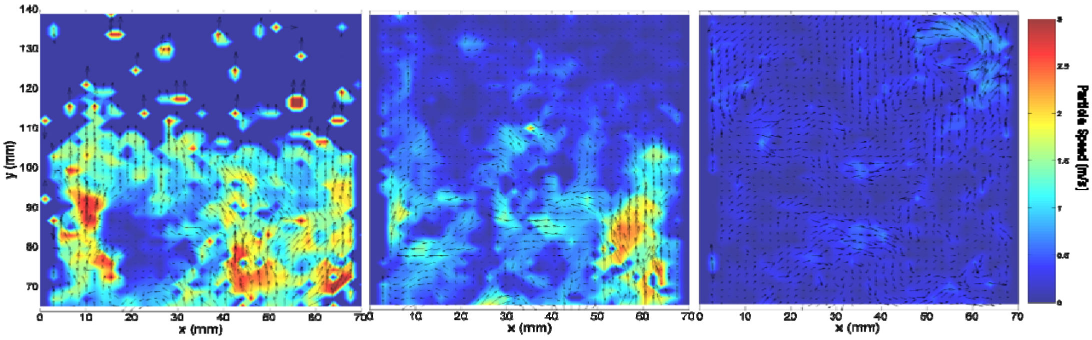


Figure 1: Diagram showing the experimental set-up for PIV analysis in a squared-section vertical tube



A. 38 ms **A.** 105 ms **B.** 238 ms

Figure 2: Velocity vector fields obtained from PIV analysis for different times A: 38 ms, B: 105 ms and C: 238 ms after the dispersion of 78 mg of starch

The modified Hartmann tube was used to deliver an air pulse of 7 barg at the bottom of the tube, where the dust is initially placed in a stainless-steel cup. The PIV system (Dantec Dynamics) is composed of a computer, a laser providing a double pulsed light sheet of 0.25 mm thickness, a CCD camera (Kodak Mega plus ES.1.0) with a 1,008×1,016 pixels resolution and a synchronizer, which acts as an external trigger to control both the camera and the laser. Two pictures of the dust cloud are taken every 66.7 ms (+150 µs) at heights ranging from 6.5 cm to 14 cm on the full width of the tube. The Phantom camera was used to visualize the dust dispersion and to characterize the dispersion time through the comparison at different time steps of the pictures taken by 'Camera 1' (Figure 1). In situ particle size measurements were also performed by using a laser diffraction sensor (Helos – Sympatec) to validate CFD simulations (Murillo et al., 2013a).

Extensive sets of experiments were executed to obtain statistically relevant data as shown on Table 1 in order to calculate the mean velocity $\bar{u}$. The turbulence intensity is then defined as the ratio of the root-mean-square velocity u_{rms} by $\bar{u}$ (Dahoe, 2000). Wang et al. (2006) have also performed such an experimental study in order to determine the turbulence intensity in an explosion tube. However, the dispersion system was different. In our case, through PIV analysis it was possible to estimate more than 7 velocity vector fields for each experiment at different moments after dispersion as illustrated in Figure 2.

Table 1: Summary of experiments performed by PIV. Laser pulse delay is the time between the acquisition trigger order and the first laser flash

Dust specificities			PIV parameters		
Product	d_{50} (μm)	Mass (mg)	Tube section (cm)	Laser pulse delay (μs)	Number of experiments
Wheat starch	25	78	6.5 - 14.0	150	70
Wheat starch	25	319	6.5 - 14.0	150	70
Glass	86	5	5.0 - 12.5	100	20

2.2 CFD simulations

A complementary approach was considered to analyze the dust dispersion and determine the turbulence levels of the two-phase flow. For this purpose, a numerical description of the transient behavior of the flow variables was performed with a Computational Fluid Dynamics (CFD) simulation (Ansys Fluent). The two-phase flow simulation was based on an Euler-Lagrange approach. With regard to the high solid loading, particle/particle interactions and the potential fragmentation or agglomeration phenomena were taken into account.

In a previous study, the main characteristics of the computational analysis were specified according to the operation protocol of the standardized apparatus (Murillo et al., 2013b). Afterwards, a definition of the numerical parameters and the initial and boundary conditions of the two phases inside the modified Hartmann tube was constituted. This approach describes the development of the main flow variables during a flammability test and characterized the vorticity structures and the segregation levels of the solid phase inside the tube (Murillo et al, 2013a). CFD simulations were corroborated and validated by experimental results. Other authors have performed similar CFD simulations on the 20 L explosion sphere (Di Sarli et al., 2013).

3. Experimental results

The vertical and horizontal components of the velocity were analyzed in order to characterize the evolution of the turbulence in the tube. Therefore, it was necessary to estimate u_{rms} from the fluctuating velocity u' and thus to calculate of the mean values of the vertical and horizontal components of the velocity u. Nonetheless, for the estimation of $\bar{u}$, special considerations were required due to the unsteady nature of the phenomenon. For the horizontal velocity, it was assumed that the mean value is constant and equal to zero, which is in rather good agreement with the experiments (Figure 3 - right). For the vertical mean velocity, it was necessary to perform a thermodynamic analysis of the air decompression. Then, the settling of dust particles, which requires the balance of drag and buoyancy forces acting on them, was taken into account. Both analyses were coupled to obtain an analytical model, which has been used to fit the experimental data (Figure 3 - left).

Finally, turbulence intensity was studied and the data obtained, some of which are presented in Figure 4, allow to better understand the behavior of turbulence caused by the dispersion of dust inside the tube. It must be noted that, most of the times, dust has not achieved its maximum height before 50 ms (Figure 4A). Therefore, the comparison of turbulence at different heights is difficult before that moment. Moreover, the high points prior to 50 ms are obtained for small quantities of particles that sometimes achieve these heights in a short period of time. Thus, due to the speed of these few particles and the small concentration, turbulence seems to be high there. Nevertheless, after 50 ms and until 250 ms a considerable difference of turbulence intensity exists at the different heights analyzed (Figure 4B-D). This suggests that conditions are considerably uneven specially when, for instance, turbulence intensity at 6.5 cm can double or triple that at 14 cm. This aspect should be considered when comparing data of flame propagation in other experimental set-ups where, even if geometrical conditions are similar, the way the dust dispersion is performed may be considerably different (Di Benedetto et al., 2011). After 250 ms most of the heavier/bigger particles have already settled to the bottom of the tube and thus the smallest particles that are more sensitive to drag forces, but also to ignition, are still dispersed in air (Figure 4E). This explains the uniformity achieved for turbulence intensity at all heights but further analysis becomes irrelevant at that point as most of the mass is already absent.

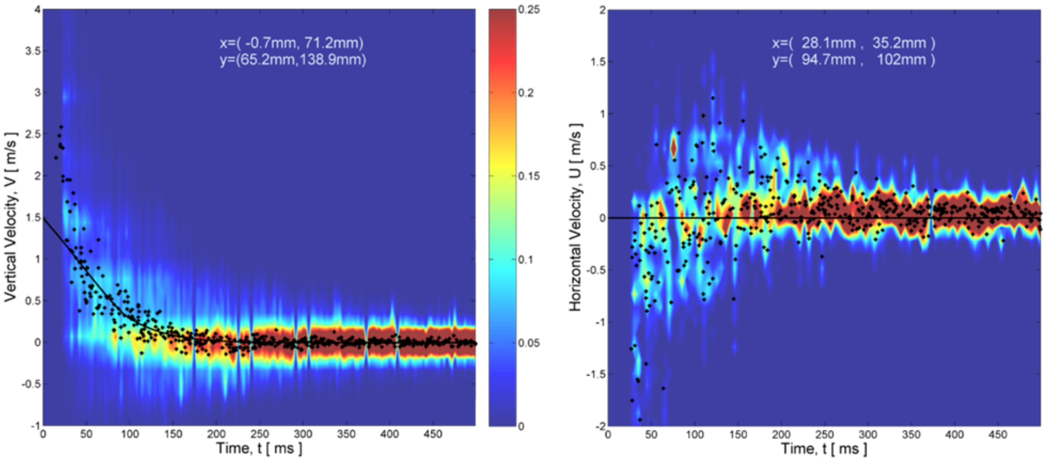


Figure 3: Vertical (left) and horizontal (right) velocities versus time in a square tube for 70 dispersions of 78 mg of wheat starch. Black points represent the mean velocity in the coordinates indicated for one vector field captured

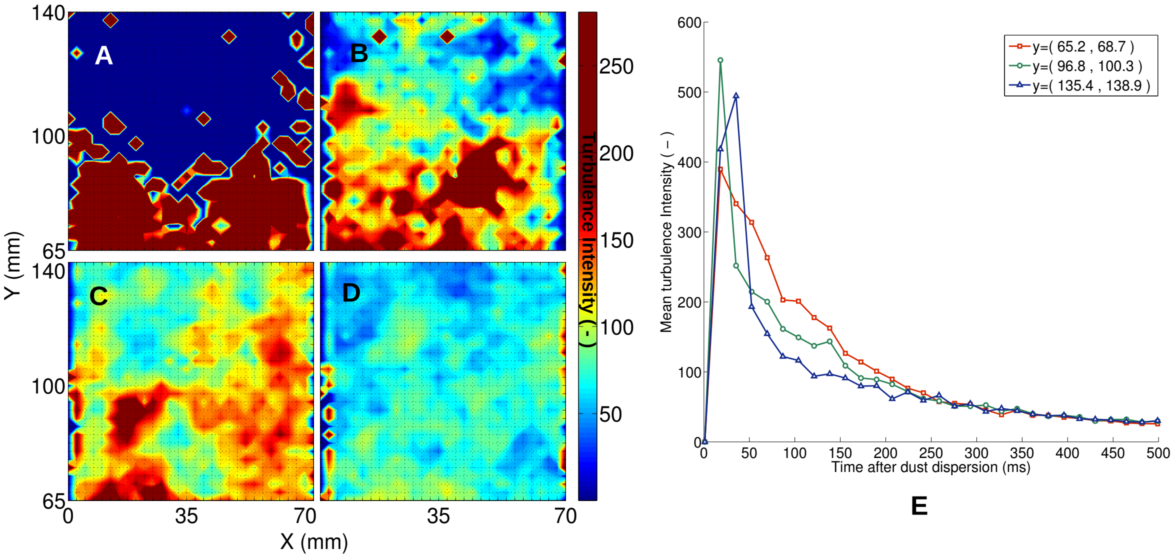


Figure 4: Turbulence intensity behavior in time for the dispersion of 78 mg. A: 21 ms; B: 61 ms; C: 121 ms D: 182 ms; E: mean turbulence intensity at different heights y in the tube.

4. Comparison of PIV and CFD simulation

The results obtained in this study determine a behavior of the gas flow which characteristics correspond to the data acquired experimentally through the PIV analyses. The injection of the air pulse determines a velocity field that evolves with the pressure decrease of the rising gas. This fact constitutes an aspect of interest for the definition of some design and operating parameters such as the height of the electrodes and the ignition delay tv.

The pressure-time histories shown in Figure 5 for two heights evidence two peaks which correspond to the temporary presence of the bulk of the dust cloud. This spatiotemporal propagation of the dust cloud has been confirmed by observations with the high speed video camera. It also demonstrates that the dust cloud shows higher instabilities for the lowest heights, which is consistent with the PIV measurements highlighting the presence of turbulent eddies causing large fluctuations in velocity near the bottom of the tube.

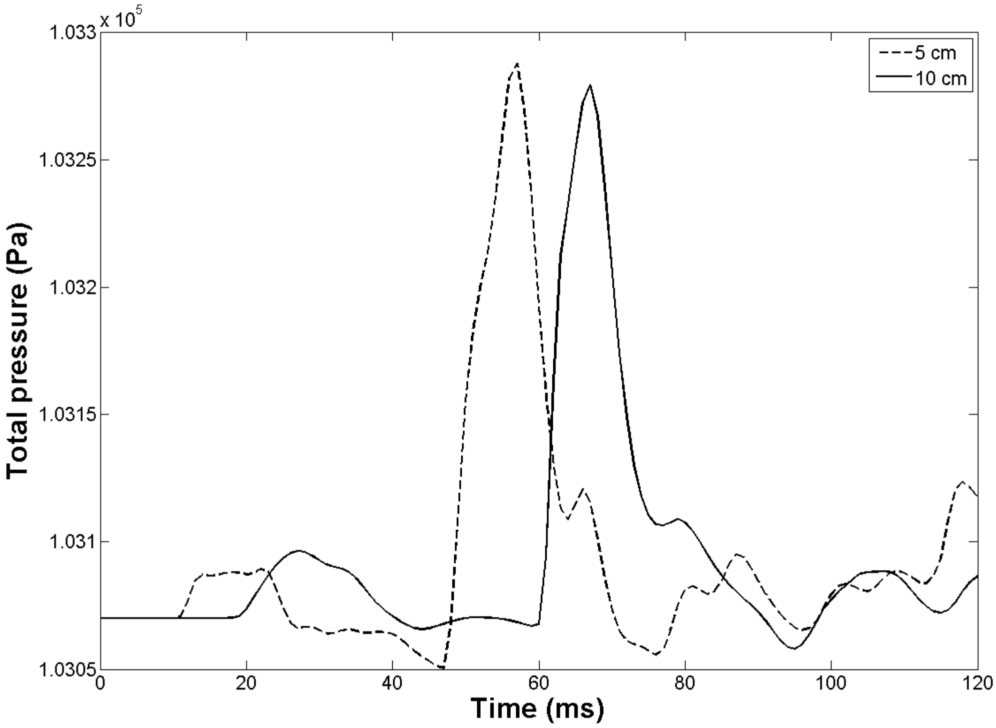


Figure 5: Mean pressure profiles at different heights of the vertical tube

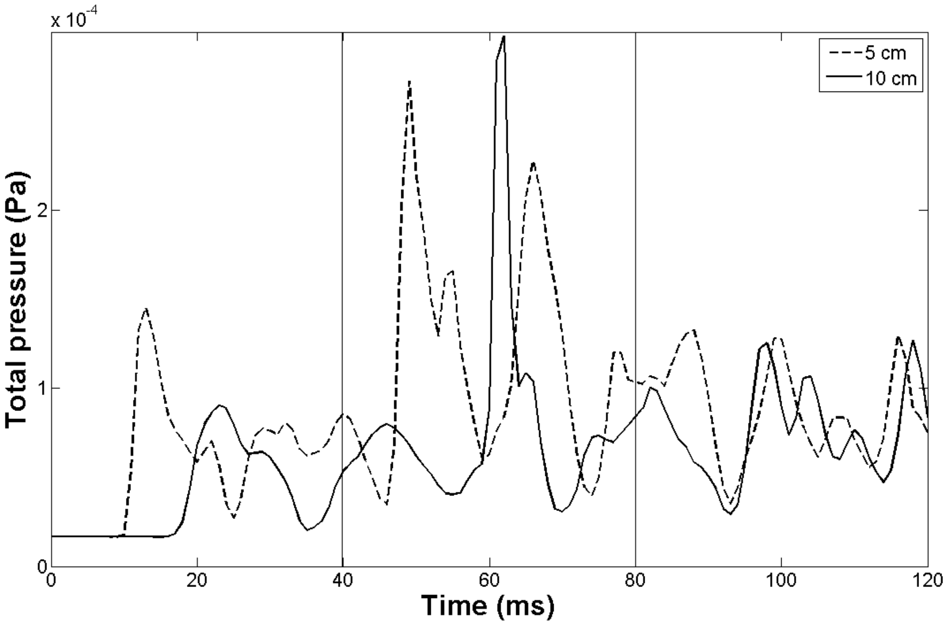


Figure 6: Variations of the effective viscosity of the gas flow

These simulations also confirm that the dispersion process can be decomposed into three stages (Bozier 2004). The first stage corresponds to the opening of the outlet valve and to the gas injection. The velocity vectors are mainly directed in the vertical direction, which denotes the presence of powerful air jets. The turbulence intensity increases greatly up to 500 %, notably at the height of the electrodes (12.5 cm) (Figure 4E). Moreover, due to the geometry of the dispersion nozzle, particle recirculation occurs at the lower end of the tube. During the first 40 ms, the bulk of the dust cloud rises with a maximum velocity of approximately 3.2 m/s. In the second stage of the dispersion, the velocity vectors are less oriented and the pressure levels in the tube tend to become more uniform after 120 ms (Figure 5). The fluctuating velocities as well as the turbulence intensity gradually decrease. On Figure 4E, this trend is more visible after 200 ms, time after which the behaviors became similar for every height of the tube.

Then, if the ignition delay tv is chosen within this time range (from 100 to 200 ms), this can improve the homogeneity of the dust cloud and lead to a conservative and appropriate turbulence level for the determination of the flammability parameters of a combustible dust. The third stage corresponds essentially to the particles settling, with velocity vectors oriented downwards and settling velocities of a few cm/s.

Figure 6 shows that the effective viscosity of the gas undergoes several fluctuations for positions located at 5 and 10 cm over the dispersion nozzle. The gradual increase of the turbulence levels is visualized through the variations of the momentum transfer represented by the effective viscosity of the turbulent flow. Figure 6 also clearly shows that the time-distribution of the effective viscosity is wider at heights lower than 10 cm (5 cm and 2 cm - not shown here). For this reason, the electrodes should be installed at 10 or 15 cm over the dispersion nozzle in order to get more precise and reproducible results during a standard flammability test. These numerical results are consistent with those obtained experimentally and demonstrate that the lowest part of the tube has longer periods of high turbulence because of the continuous rise of the dust cloud. Finally, they confirm that the ignition delays greater than 100 ms might be more appropriate in terms of dust cloud homogeneity and then tests reproducibility.

5. Conclusions

The comparison of CFD simulations and PIV measurements performed on an explosion tube has proven to be useful to validate the numerical approach and to determine the influence of various parameters on the characteristics of the dust dispersion: local concentrations, particles velocities, turbulence intensity... In this article, the influences of the ignition delay and of the electrodes height have been approached; other effects have been tested such as the initial pulse pressure or the nozzle geometry.

In the short term, these results will improve our predictive models on dusts explosions. In a longer term, this study will advocate modifications of the existing procedures/standards in order to define the most relevant suspension characteristics, only by knowing the powder properties.

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