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CFD Simulation of Multiple Dust Explosion Occurred in a Flour Mill

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Dust explosions pose a serious hazard to both personnel and equipment in industries that handles combustible powders. Although prevention and mitigation technology of dust explosions has progressed greatly, continual accidents in the process industries demonstrate the need for improved knowledge in this area (Mercan, 2016; Russo et al., 2017). On July 16, 2007, a primary explosion followed by secondary explosions happened in the Cordero mill (Italy) and 5 persons died (Marmo et al., 2012). The accident occurred at the end of the loading operation of a tanker, when a surplus of flour was overcharged. This extra amount was then pneumatically conveyed to a silo placed in the flour-warehouses, by connecting the tanker to the pneumatic transport line through one of the tanker hoses. The flour was loaded at a low flow rate, and hence a low concentration of flour in the duct occurred. The source of ignition of the dust cloud was attributed to an electrostatic arc that took place in the pneumatic transport duct (Marmo et al., 2012). The technical enquire found signs of the explosion in the duct: internal pressure provoked evident deformation of the duct. As widely discussed in the literature (Fiorentini and Marmo 2019; Marmo et al., 2013), Computational Fluid Dynamics can be a valid aid to forensic engineering because it allows to discern the incidental sequence that is more adherent to the evidence. The aim of this work is to reproduce the conditions present in the mill at the time of the accident using the CFD-code DESC, which is being developed for simulating dust explosions in complex geometries. The results obtained from the simulations were compared to the damage observed after the accident in order to identify the more credible scenario. Simulations with different levels of flour in the silo, concentration of dust in the air mixture and position of ignition were performed. Analysis of results revealed the effect of different parameters on the severity of dust explosion, not only limited to the case study investigated, in order to adopt the appropriate prevention and protection measures.

1. Case study

1.1 Plant description

The flour mill Cordero was located in the town of Fossano. It was constituted by a main rectangular masonry building of four storey plus a basement and a more recent three-storey construction where were located the products warehouse and the offices. Along the length of the building, on one side there was a large courtyard for the movement of vehicles and on the other side a second courtyard was near a road in the village. The production area was located in the main building, where the four main sections were separated by brick thick walls. Entry to the rooms was through an internal staircase and a hoist. The "B" rooms were used to produce wheat flour, and the "A" rooms for the flour storage and for the preparation of the wheat for milling operations. A plan of the basement of the main building is reported in Figure 1.
The other floors were similar. Leaning against the East wall (towards the sacks warehouse) there were two metal flour silos that rose up to the second floor. Nearby there were bucket elevators. Against the middle wall of the building there were, from west to east, a freight elevator and 6 flour silos (the first was made of metal, the other made of wood) that rose up to the top floor and several bucket elevators. In the basement there was

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a fabric silo supported by a metal frame. The floor was made of concrete with a steel beam structure. The floor of the 4th level was made by wooden planks.

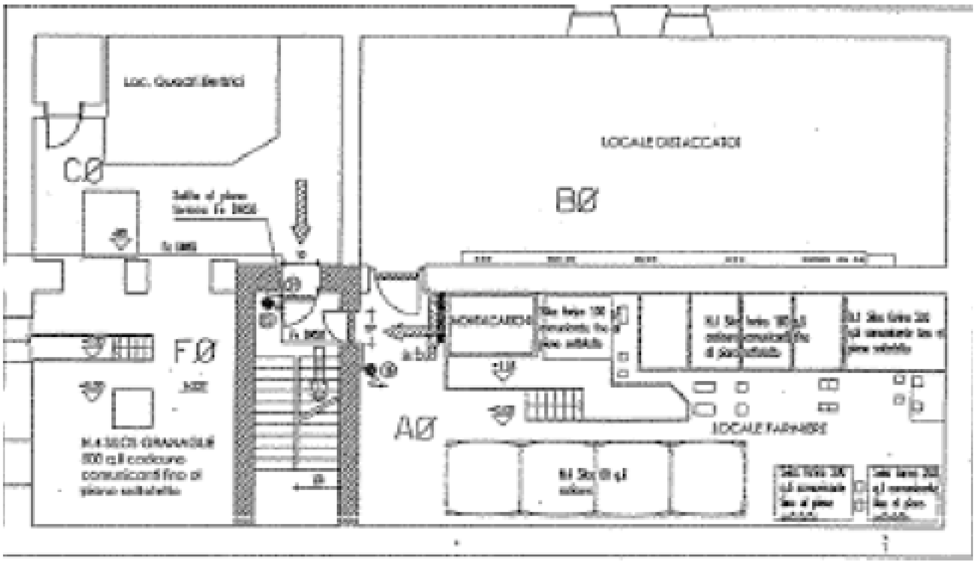


Figure 1. Plan of the basement of the main building.

1.2 The accident

On July 16, 2007, a tanker was loaded of flour transported by a bucket elevator to a cochlea and by gravity fall. The accident occurred at the end of the loading operation of the tanker, when a surplus of flour was overcharged. This extra amount was then pneumatically conveyed to a wooden silo placed in the flour-warehouses, by connecting the tanker to the pneumatic transport line through one of the tanker hoses. The flour was loaded at a low flow rate, and hence a low concentration of flour in the duct occurred. During loading and unloading operations the truck was not grounded. The technical enquire ascribed the ignition of the explosion to an electrostatic arc that took place in the pneumatic transport duct (Marmo et al., 2012). Specifically, it found evident signs of the explosion in the duct which was deformed by internal overpressure. After the ignition, the flame front arrived immediately to the silo where the flour was being conveyed. Since the large amount of suspended flour present in the silo, a very strong secondary explosion occurred, and then spread to other zones of the building.

1.3 The damage

In Figure 1, A and B are the areas of the main building of the mill which underwent a considerable, but not complete, collapse.

In the basement, the collapse of all the B rooms and of their equipment occurred. Most of the equipment (i.e. plansicthers, mills, cyclones, cochlea and elevator ducts) was not burned by the fire. With regards to the walls, the north one collapsed, but the internal ones were only damaged. Also, the stability of internal staircase, which was found in its original position, was compromised.

On the contrary, in the A area of the basement the walls and equipment were primary damaged by the fire, which had burned over a long period of time (Figure 2). The internal overpressure caused damage to the ceiling of A0 area as well as that of the A1 area (Figure 2). The hoist bay was destroyed by internal overpressure, while the overpressure from the hoist caused major damage to the structures on the side of the building.

The roof above north and south wings was torn away and projected at a considerable distance. Debris launch distance is much higher toward south than toward north as the rooms on the A side were certainly affected by a strong internal overpressure of intensity depending on the altitude, which caused obvious projections of the structures and debris towards the outside and upwards. On the contrary, the rooms B were mainly affected by a static collapse that has caused the collapse of the structure and the machines: in fact, most of the rubble is located within the perimeter or very short distance. All the other rooms were marginally affected by the explosion, while some, like the sacks warehouse, suffered from the long fire that followed the explosion.

Figure 2. Damage of the main building from the exterior (a) and inside the A area (b,c).

With regards to the transfer pipe from the truck to the silo, some parts were found in their original place, but other parts were found from the debris heap and some were lost. Moreover, the flanges of the pipe showed the typical deformation due to high internal pressure. Because of the overpressure, the material suffered much higher stresses than the elastic limit, and thus a permanent deformation.

2. CFD simulations

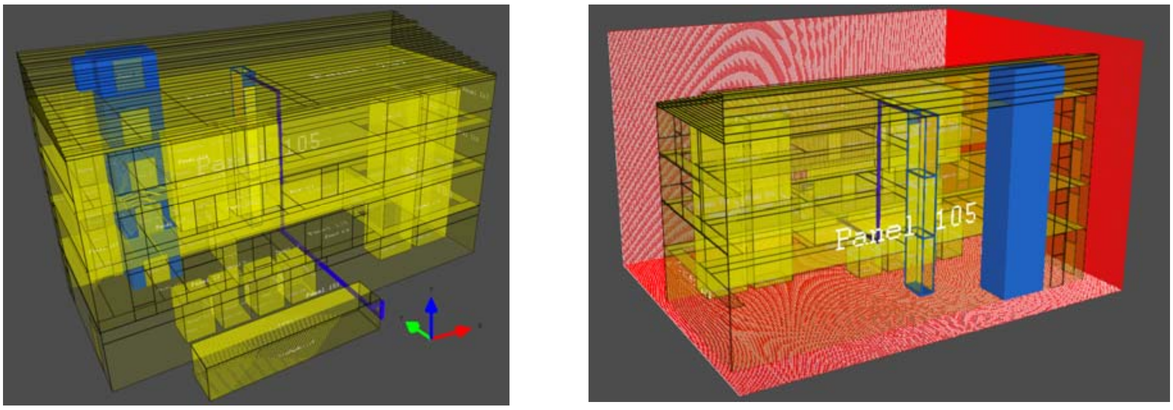
2.1 DESC code

DESC (Dust Explosion Simulation Code) was a CFD code developed to simulate dust explosions in industrial complex geometries (Skjold and Eckhoff, 2016). Skjold et al. (2005, 2006) simulated with DESC large-scale dust explosion experiments in silos. This model was a modified version of a CFD code called FLACS (Flame Acceleration Simulator) which was developed for the simulation of gas explosions. It has estimated potential overpressures in several case studies and accidents (Russo et al., 2017). The code solves the Reynolds-Averaged Navier- Stokes (RANS) equations for mass, enthalpy, momentum, and species. The RANS equations are closed using the k-ε turbulence model. The combustion model consists of a flame model and a burning velocity model. In DESC, the burning velocity model entails that the laminar burning velocity is roughly estimated from measured pressure-time curves in a 20-litre vessel. The code was based on a finite volume technique with a weighted upwind/central differencing scheme for the convective term. First-order time integration was used. The time step was limited according to the default values of CFLC and CLFV numbers, which for explosion simulations are CFLC =5.0 and CFLV = 0.5, which means that in each time step the pressure can propagate 5 cells and the flow 0.5 cells.

2.2 Simulation parameters

The geometry of the A area of the main building (28.2x11.7x17.0 m^3) was reconstructed in DESC with CASD code as shown in figure 3. The grid used is uniform and the cell size is 10 cm with a total of 12,217,500 cells to obtain accurate results inside the simulation volume (Figure 3). Some objects of the A area, which include the roof, the windows, the doors, some walls and the floor of the building and the walls of the silos, are represented by pressure relief panels. These devices allow to define objects with a dynamic behaviour when overpressure is detected on the surface of the panel. The characteristics of the panels (267 in total) are reported in Table 1 as obtained from NFPA 921 (2008). The fuel properties were set defining cloud volume, dust concentration, and thermodynamic and chemical data of fuel. The explosion parameters (P_{max}=8.6 barg, K_{st}=150 bar m/s) of dust are those reported in literature for wheat flour (Mittal, 2013), as obtained in 20-L

sphere. This is the standard apparatus for dust explosion tests, through the generation of a uniform dust/air cloud inside the vessel (Di Sarli et al., 2015; Sanchirico et al., 2015).
In the simulation only the first explosion was considered. The dust cloud was assumed to fill the pipe, used to transfer the flour from the trucks to the warehouse, and the silo. Simulation were run by changing the dust concentration in the pipe and in the silo in the range 250- 2000 g/m^3, and by changing the volume of dust cloud from 1/3 to 2/3 of the volume of the silo. The bottom part of the silo (1/3 of the volume) was assumed to be completely full of flour. The ignition source, with an energy of 10 mJ, was located at different heights inside the silo (i.e. at bottom (3.55m), at half height (7.25m), and at the top (9.25m) of the silo).



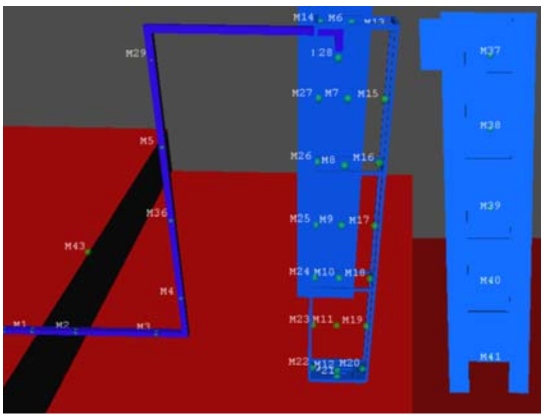
a) b)

Figure 3. Geometry of the A area of the building (a) and grid (b) used in simulations.

Table 1: Characteristics of pressure relief panels

Object	Failure pressure (barg)	Weight (kg/m^2)
Glass windows	0.03	10
Fire protection doors	0.07	157
Hoist doors	0.07	395
Brick walls (20 cm thick)	0.48	1800
Concrete floor	0.25	625
Wooden silo walls	0.20	25
Roof panels	0.14	40
Under-roof panels	0.14	50

To follow the value of parameters as temperature, maximum pressure (P_{max}), dust concentration, velocity in time and space, some monitors points were set inside the simulation volume. The monitors were located inside the pipe, the silo, the roof, the hoist and the good receipt area as shown in Figure 4.



Monitor Point	Position
1 to 5, 29 to 36	Pipe
6 to 28	Silo
43	Goods receipt area
42	Under-roof area
37 to 41	Hoist

Figure 4. Positions of the monitor points.

3. Results

Simulations were performed for various scenarios with different levels of flour in the silo, concentration of dust and position of ignition. The overpressures predicted for each scenario in the different monitor points were compared with the failure pressure of the various objects. From the comparison, it was possible to define the scenario that is compatible with the damage observed after the explosion. It corresponds to the scenario with the silo only partial filled with flour (1/3 of volume), concentration of dust in the dust cloud of 2000 g/m^3 (higher than the stoichiometric value) and the ignition at the top of the silo. Results of the simulations were reported in figure 5 for this scenario. They showed that it can predict: the collapse of the silo, because of the overpressure increase along the silo length from the top (P_{max} = 0.15 barg) to the bottom of the silo up the failure value (P_{max}>0.20 barg). Moreover, it can describe the propagation of the blast wave into the pipe and, as consequence of the silo collapse, then in the goods receipt area, where the under-roof and of roof panels fell. The propagation of the blast wave to the hoist, from the top to the bottom, with the collapse of the hoist door (P_{max}>0.07 barg), and then to the basement where overpressure as high as 0.27 barg caused the collapse of the concrete floor (Figure 6) and consequently of the flour bins. The large amount of dust dispersed in the area, because of the poor housekeeping, ignited by the blast wave, was then the cause of multiple explosions occurred in the plant.

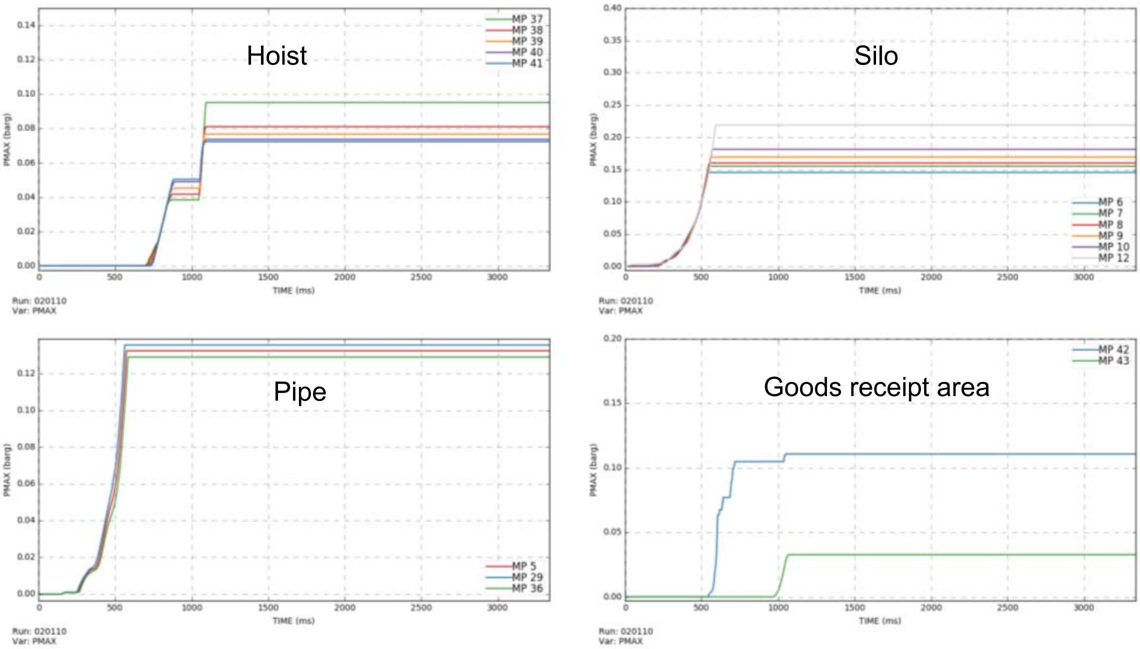


Figure 5. P_{max} vs time in the monitor points located in the hoist, silo, pipe and goods receipt area.

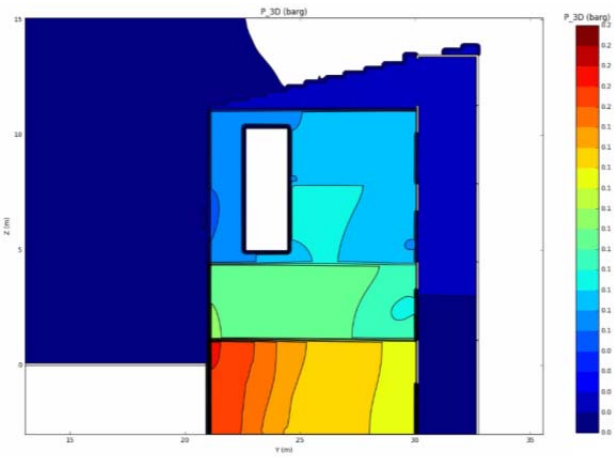


Figure 6. Map of P_{max} reached in the hoist and in the basement (at 960 ms).

4. Conclusions

The case study here analysed showed that ordinary and unusual operations, especially those of loading and unloading silos, bins, storage houses are the recurrent cause of uncontrolled explosions. Proper procedures should be defined when such operations have to be carried out in order to reduce the risk of explosions. Deflagration venting can reduce the impact of dust cloud explosions by controlling the release of the explosion energy. Damage to the remaining structure and equipment is then minimized. Good housekeeping in processing areas is important to prevent and mitigate dust explosions. In particular, to prevent secondary dust explosions, dust accumulation has to be minimized. Designing and maintaining equipment to prevent dust leaks, using dust collectors, eliminating flat surfaces and other areas where dust can accumulate, ensuring good housekeeping, and sealing hard-to-clean areas (such as the area above a suspended ceiling) can effectively prevent secondary dust explosions. Moreover, this paper demonstrates that computational fluid dynamics can be a valid aid to forensic engineering because it allows to discern the incidental sequence that is more adherent to the evidence. This despite the investigation must necessarily base the bases on a solid activity of evidence collection.

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