Simulating Vented Maize Starch Explosions in a 236 m^3 Silo

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ABSTRACT

The paper describes computational fluid dynamics (CFD) simulations of a series of large-scale dust explosion experiments performed in a 236-m^3 silo. Mechanical suspensions were generated by pneumatically injecting maize starch into a 22 m high silo. The experiments included tests with injection from the bottom and from the top of the silo, but the present study only considers bottom injection. The clouds were ignited at various heights above ground. The same experiments have been simulated previously, but the current work involves an updated version of the CFD code and explores the effect of grid resolution on the simulation results. The results from the simulations are in good agreement with the experimental data, and confirm the observation that the reduced explosion pressure in long slender silos is very sensitive to ignition location. The simulation results highlight the effect of dust distribution within the silo, and reproduce the characteristic pressure oscillations, with frequency in the range 4-7 Hz, observed in some of the tests.

KEYWORDS: explosion, modelling, dust explosion, ignition location, risk assessment

NOMENCLATURE

A_v	Vent area on enclosure (m^2)
c_d	Actual dust concentration (kg m^{-3})
c_{nom}	Nominal dust concentration, $m_d V_v^{-1}$ (kg m^{-3})
E_{ig}	Ignition energy (J)
h_{ig}	Ignition location above silo bottom (m)
K	Karlovitz stretch factor (–)
K_{St}	Size-corrected maximum rate of pressure rise, $(dP/dt)_{max} V_v^{1/3}$ (bar m s^{-1})
ℓ_e	Turbulent integral length scale (m)
m_d	Mass of dust (kg)
p	Absolute pressure (bar*a*)
P_{max}	Maximum explosion pressure (bar*g*)
P_{red}	Reduced explosion pressure (bar*g*)
S_f	Flame speed (m s^{-1})
S_L	Laminar burning velocity (m s^{-1})
S_T	Turbulent burning velocity (m s^{-1})
S_u	Burning velocity, general (m s^{-1})
T	Absolute temperature (K)
t_v	Ignition delay time (s)
u'_{rms}	RMS turbulent velocity fluctuations (m s^{-1})
V_v	Volume of enclosure (m^3)

Greek

Δ_g	Size of cubical grid cells (m)
δ_f	Flame thickness, general (m)
δ_L	Laminar flame thickness (m)
δ_T	Turbulent flame thickness (m)

Subscripts

$_d$	Dust
$_f$	Flame
$_F$	Fuel
$_g$	Grid
$_{ig}$	Ignition
$_{ip}$	Inflection point
$_L$	Laminar
$_T$	Turbulent
$_u$	Un-burnt
$_v$	Vessel

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INTRODUCTION

Dust explosions pose a hazard whenever a certain mass of combustible material is present as fine powder, the powder can be dispersed in air to form an explosive dust-air cloud within a sufficiently confined and/or congested volume, and there is an ignition source present. Figure 1 shows the explosion pentagon, which summarizes the factors required for chemical fuel-air explosions [1]. Processing of combustible powders takes place within closed units, such as mills, dryers, filters, elevators, conveyors and silos, and explosive atmospheres can be present during normal operation. Although the technology for preventing and mitigating dust explosions has progressed considerably over the last 150 years [2], recurring accidents in the process industry demonstrate that there "remains much to be done before dust explosions are adequately understood" [3]. Explosion venting is a widely used mitigation method in industry, whereby destructive overpressures are prevented by designing parts of the equipment to fail during early stages of the explosion, allowing unreacted mixture, flames and combustion products to escape to the surroundings [4-6].

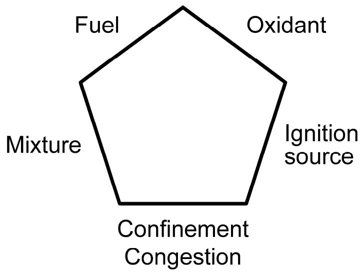

Fig. 1. The explosion pentagon.

Flame propagation in dust clouds entails "premixed combustion with non-premixed substructures" [7], and detailed modelling from first principles is a formidable task. Hence, venting and other methods for mitigating the consequences of industrial dust explosions rely on empirical correlations [8-10]. The relevant explosion parameters for a given dust sample are determined in standardized tests performed in constant volume explosion vessels [11-17]. However, the process of generating the mechanical suspensions in such experiments entails transient turbulent flow conditions that complicate the task of determining fundamental combustion parameters, such as burning velocity S_u and flame thickness δ_f [18-31].

In order to predict the consequences of dust explosions and optimize mitigating measures in more complex geometries, it is foreseen that the state-of-the-art in explosion protection will shift towards increased use of computational fluid dynamics (CFD). Previous work has demonstrated that simulation tools may take advantage of combustion parameters determined in standardized tests [27]. However, further progress on the numerical modelling approach requires reliable data from repeated large-scale experiments, as well as improved understanding of the inherently complex phenomena involved in dust explosions: transient turbulent flow and combustion in mechanical suspensions of finely divided solid material dispersed in air, in more or less complex geometries [32-33].

With respect to CFD modelling, it is convenient to introduce parameters such as turbulent burning velocity S_T and turbulent flame thickness δ_T, and to correlate these with more fundamental parameters characterizing the thermodynamic state (absolute pressure p and temperature T), dust concentration c_d, flow conditions in the mechanical suspension (root-mean-square of the turbulent velocity fluctuations u'_{rms} and a representative turbulent length scale ℓ), and combustion properties at some reference state (usually the laminar burning velocity S_L and laminar flame thickness δ_L at ambient conditions) [27, 31].

The present paper compares results obtained with the latest version of the CFD code DESC (Dust Explosion Simulation Code) with experimental results from a classical series of silo experiments performed by Eckhoff and co-workers at the Stordalen test site in Norway [34-35]. Although these and similar experiments have been simulated with other CFD codes in the past, including earlier versions of DESC, [2, 36-41], it is nevertheless worthwhile to revisit the tests in the 236-m^3 silo. These experiments represent the state-of-the-art in experimental investigations of dust explosions, the model system in DESC has evolved through years of validation and consulting work, and the simulations presented here follow the latest grid guidelines and include a sensitivity study with respect to the spatial resolution Δ_g of the computational grid.

EXPERIMENTS

Figure 2 illustrates the experimental setup, including injection locations, ignition positions, pressure probes (P1-P3), and dust concentration probes (C1-C6), and shows a summary of the overall results. The silo was 22 m high and 3.7 m in diameter. Two different vent areas were used: 3.4 and 5.7 m^2. Explosive clouds of maize starch were generated in three different ways by conventional pneumatic conveying: dust injection upwards from the silo bottom through a 5 m vertical pipe with inner diameter 0.155 m and pipe exit about 5.5 m above silo bottom (21 tests), dust injection upwards from the bottom of the silo without the 5 m pipe (five tests, not simulated in this work), and dust injection at the silo top through a horizontal pipe (18 tests, not simulated in this work). Figure 3 shows scanning electron microscopy (SEM) pictures of maize starch particles and particle size distributions measured by low-angle laser light scattering (LALLS) with a Malvern Mastersizer X – the 10, 50 and 90 percentiles are about 6, 13 and 20 μm, respectively.

The dispersed dust clouds were ignited at various elevations inside the silo. The ignition source was 50 grams of dried nitrocellulose powder, fired by a fuse head, corresponding to ignition energy E_{ig} of about 200 kJ. The average dust concentration in the silo was estimated from measurements with dust concentration probes and weighing of dust gathered from the bottom of the silo after tests. Ignition close to the silo bottom generated overpressures exceeding one bar, whereas ignition close to the vent at the top of the silo gave only marginal overpressures, about 10-20 mbar.

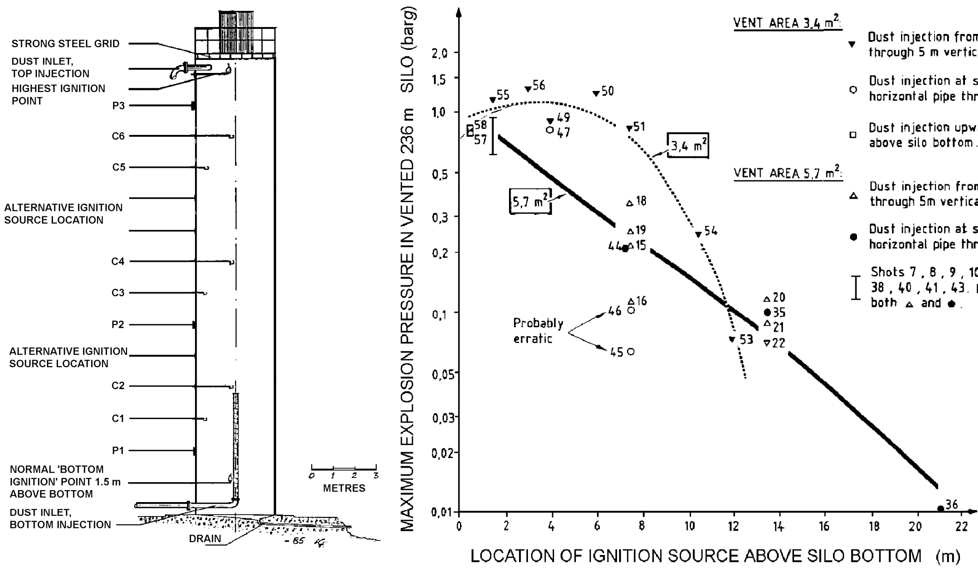

Fig. 2. Vertical section of experimental silo (left), and summary of experimental results (right) [34].

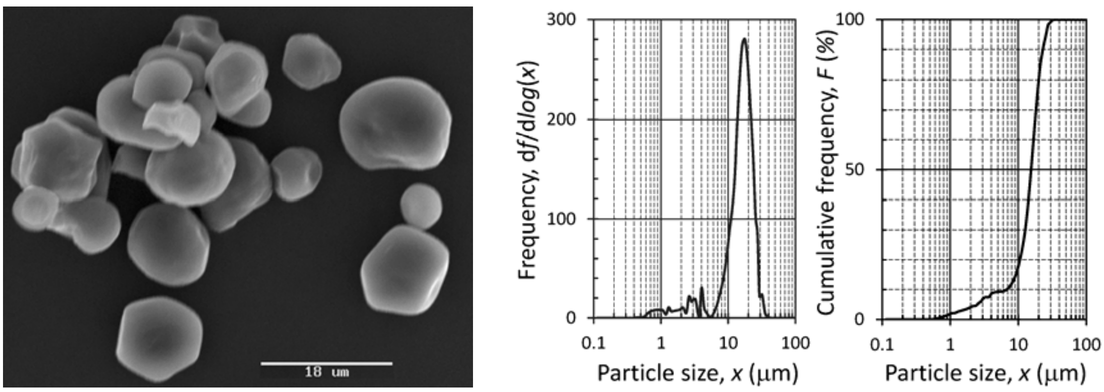

Fig. 3. SEM picture of particles and particle size distribution for maize starch of type Meritena A.

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SIMULATIONS

The simulations were performed with the CFD code DESC 1.0 (FLACS-DustEx v10.1) from GexCon. DESC solves the compressible Reynolds-averaged Navier-Stokes (RANS) equations on a three-dimensional (3D) Cartesian grid using the finite volume method. The conservation equations for mass, momentum, enthalpy and species are closed by the ideal gas law and the standard k-ε model for turbulence [42]. The modelling of particle-laden flows assumes thermal and kinetic equilibrium between the dispersed and continuous phases. The distributed porosity concept allows for the representation of complex geometries on the Cartesian grid, and includes sub-grid models for the production of turbulence by sub-grid objects [43]. The combustion model defines the reaction zone, i.e. the position of the flame, and the rate of conversion from reactants to products, i.e. the rate of energy release. The flame model gives the flame a constant flame thickness of about three grid cells (i.e. grid dependent), and ensures that the flame propagates into the reactant with a specified turbulent burning velocity S_T that accounts for the effect of reactivity (S_L), flame wrinkling, turbulence, etc. [44]. The combustion model assumes one-step reaction kinetics. The correlation used for S_T originates from empirical data for turbulent combustion of gaseous fuel-air mixtures [45], as summarized by Bray [46]:

$$\frac{S_T}{S_L} = 0.875\,K^{-0.392}\,\frac{u'_{rms}}{S_L}$$

where K is the Karlovitz stretch factor. For certain assumptions [44], including constant kinematic viscosity of 2 10^{-5} m^2 s^{-1}, the correlation from Bray may be restated as [27]:

$$S_T = 15.1 S_L^{0.784}\, u'^{0.412}_{rms}\, \ell_e^{0.196}$$

The combustion model in the CFD code uses estimates for the laminar burning velocity S_L and the fraction of fuel λ that reacts, both as a function of dust concentration, obtained from pressure-time histories measured in 20-litre explosion vessels. The calculation assumes reactants with known chemical composition, specific heat capacity and heat of combustion, and estimates product composition from simplified chemical equilibrium calculations [27]. The present simulations used the laminar burning velocity that follows from the calculations, without any corrections (i.e. a C_L factor of unity [32]).

The dispersion simulations assumed an average dust concentration in the pipe of 13 kg m^{-3} and airflow 2200 m^3 h^{-1} standard state. This corresponds to a flow velocity of 32 m s^{-1} and a total mass flow rate of 9.2 kg s^{-1}, or about 8.4 kg dust per second. The explosion simulations started from dump files created 12 seconds after onset of dust injection, when about 100 kg dust had been added to the silo. The simulations imitates ignition by converting a certain mass of reactants to combustion products – at least half the volume of the grid cell where ignition occurs, and more if the energy release of the ignition source exceeds the heat of combustion of the minimum volume.

The simulations included two grid resolutions: 0.176 and 0.264 m. This corresponds to 21 and 14 grid cells across the silo diameter, respectively. For comparison, a previous study, performed with a prototype version of DESC, used 0.5 m grid cells [38], or less than eight cells across the diameter.

RESULTS

This chapter summarizes the results from the CFD simulations.

Dispersion simulations

Figure 4 shows the coordinate system used for the simulations, and the mass fraction Y_F of fuel (maize starch) in a cross section of the silo (y = 0) at selected time steps. The figure illustrates that the flammable cloud does not reach the top of the silo, which is consistent with experimental observations. At time of ignition, 12 s after onset of dispersion, the flammable cloud reaches about 17 m above ground. It seems reasonable that a more realistic model for multi-phase flow would cause the particle-laden jet to reach somewhat higher, and future studies may explore the use of a Lagrangian model for the dispersed phase.

Explosion simulations

Table 1 summarizes the results from both experiments and simulations. The results are in good agreement, but the simulations tend to over-predict the explosion pressures for ignition in the central part of the silo. Figs. 5-8 show selected pressure-time histories from the simulations, including results from three monitor point positions for each simulation – corresponding to the pressure sensors P1-P3 in Fig. 2. The highest pressures in the simulations occur for ignition at h_{ig} = 7.5 m, i.e. in the highly turbulent flow field near the exit of the pipe. Local quenching due to high mass loading and upwards transport of the flame kernel may explain the somewhat lower pressures measured in the corresponding experiments [30]. The smaller vent opening (3.4 m^2) results in consistently higher explosion pressures compared to the larger vent opening (5.7 m^2, and the finer grid resolution (0.176 m) yields higher pressures than the courser grid (0.264 m).

Table 1. Summary of experimental and simulated explosion pressures.

A_v (m^3)	h_{ig} (m)	Experiment	Simulation: Δ_g = 0.176 (m)		Simulation: Δ_g = 0.264 (m)	
		P_{red} (bar)	No.	P_{red} (bar)	No.	P_{red} (bar)
5.7	1.5	0.66 - 0.93	115101	1.17	215101	1.00
5.7	4.5	n/a	115103	1.11	215103	0.88
5.7	7.5	0.11 - 0.35	115105	1.72	215105	1.16
5.7	10.5	n/a	115107	1.18	215107	0.80
5.7	13.5	0.07 - 0.12	115109	0.50	215109	0.35
5.7	16.5	n/a	115111	0.03	215111	0.02
3.4	1.5	1.13	125101	1.39	225101	1.30
3.4	3.0	1.27	n/a	n/a	n/a	n/a
3.4	4.5	0.89	125103	1.39	225103	1.31
3.4	6.0	1.21	n/a	n/a	n/a	n/a
3.4	7.5	0.82	125105	2.23	225105	1.74
3.4	10.5	0.24	125107	1.71	225107	1.34
3.4	12.0	0.07	n/a	n/a	n/a	n/a
3.4	13.5	n/a	125109	0.89	225109	0.64
3.4	16.5	n/a	125111	0.10	225111	0.05

DISCUSSION

Figure 9 summarizes the results from Table 1 and Figs. 5-8. The simulated explosion pressures generally over-predict the pressures measured in the experiments, particularly for ignition in the central part of the silo. It should be noted that results from large-scale dust explosion experiments tend to vary significantly from test to test [6, 32, 47-49], and various phenomena that are not modelled in the CFD code may lower the experimental pressures: fall-out of dust, agglomeration, partial flame quenching, etc. [30, 33].

The effect of grid resolution on the simulation results represents a fundamental problem for CFD codes developed for engineering applications. Since it is not realistic to resolve important physical phenomena such as turbulent flow and multiphase combustion when simulating explosion scenarios on industrial scales, the traditional approach is to prescribe grid guidelines based on theoretical considerations and validation studies. Previous validation work for DESC shows that it is possible to achieve good agreement between experiments and simulations, but that the results depend on both reactivity and grid resolution [6, 32]. Numerical solvers based on adaptive mesh refinement (AMR) represent a promising way forward with respect to reducing the effect of grid resolution.

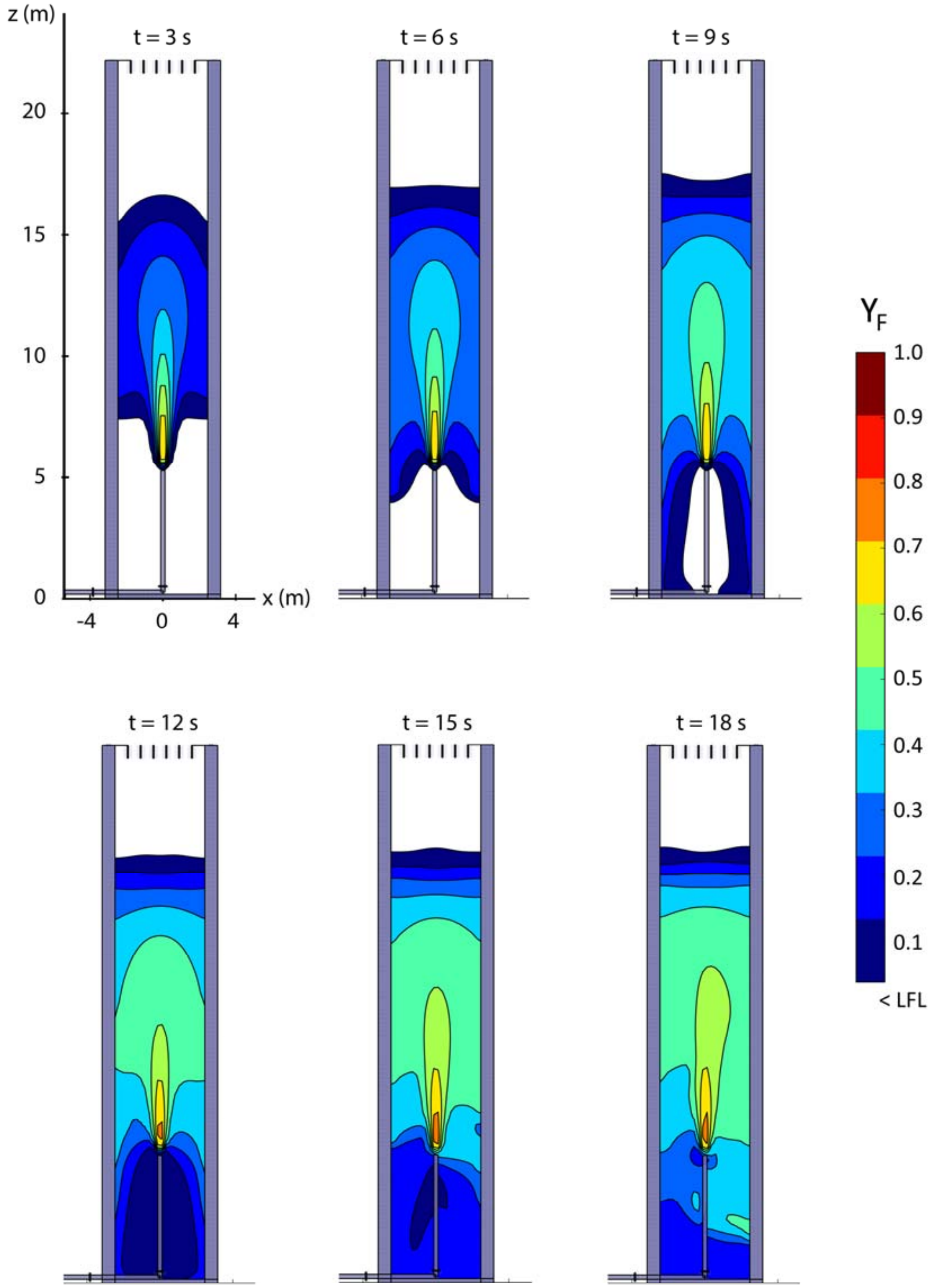

Fig. 4. Simulated mass fraction of dust at selected times during dispersion.

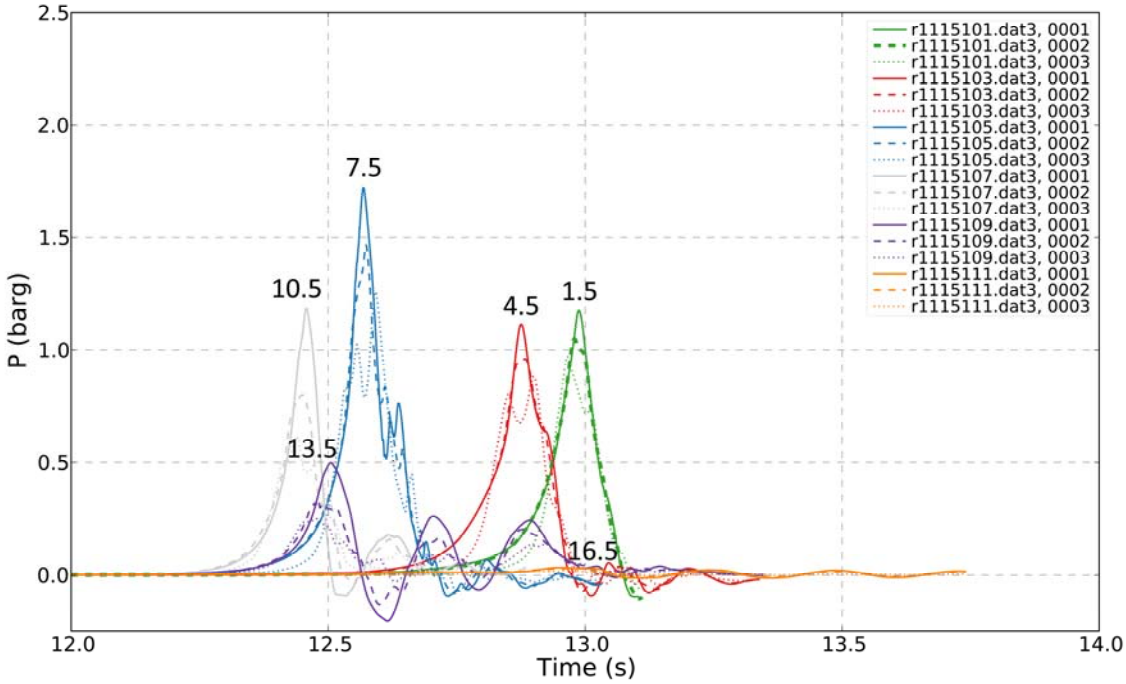

Fig. 5. Simulated pressure-time histories: A_v = 5.7 m^2, Δ_g = 0.176 m, and h_{ig} indicated for peaks.

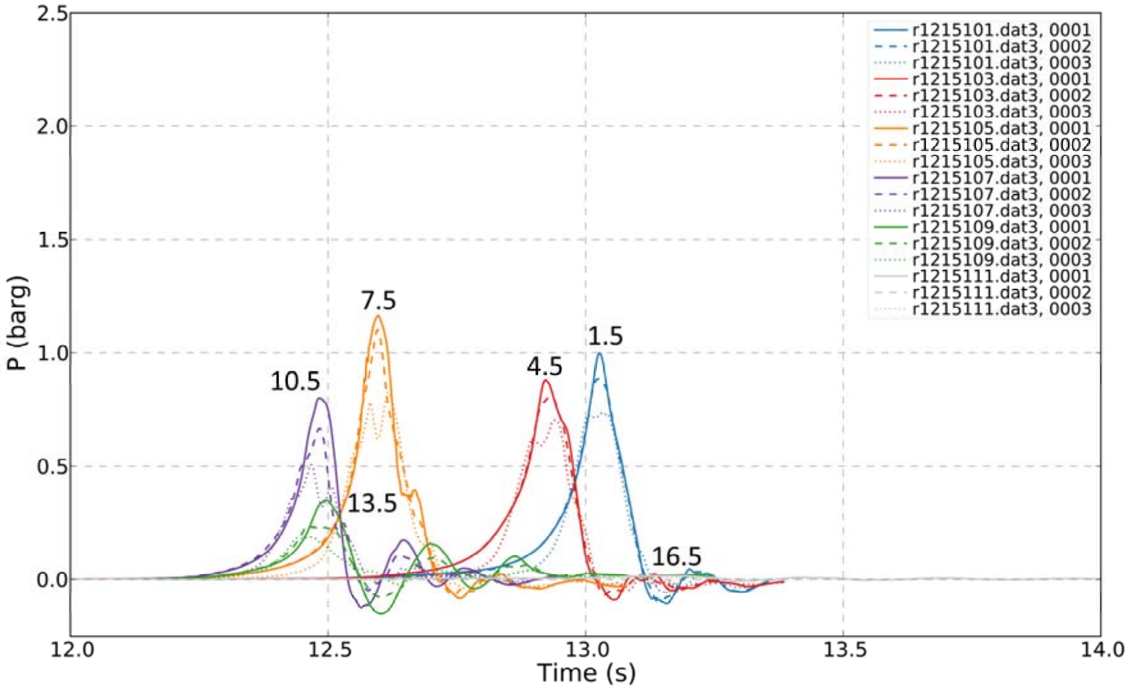

Fig. 6. Simulated pressure-time histories: A_v = 5.7 m^2, Δ_g = 0.264 m, and h_{ig} indicated for peaks.

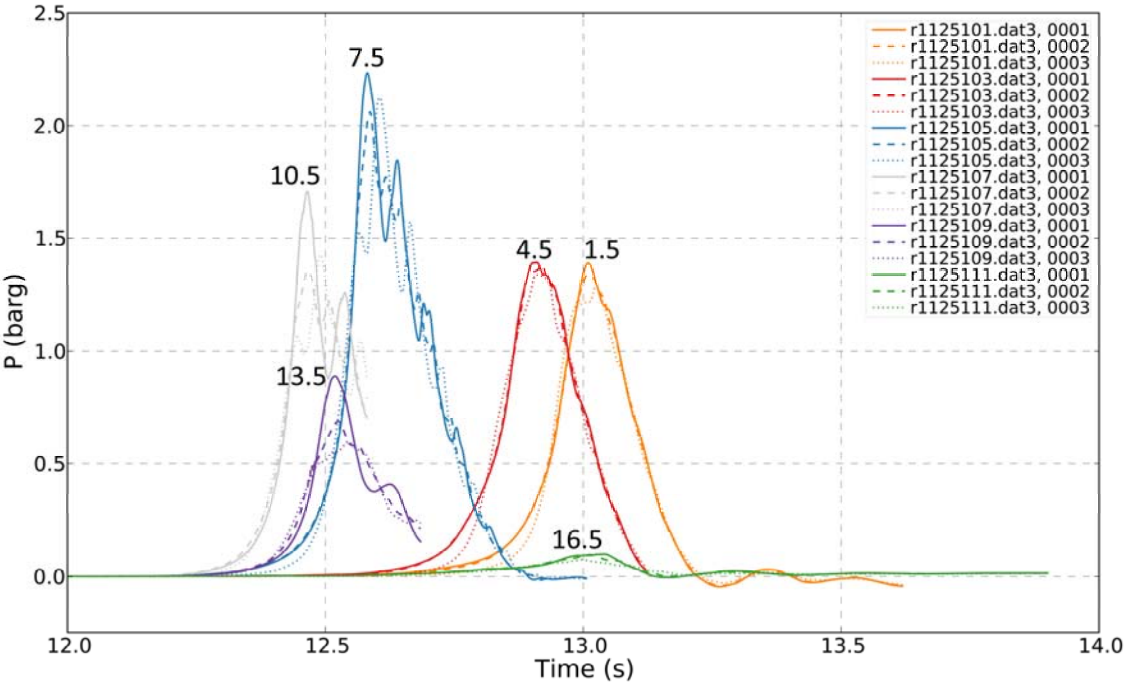

Fig. 7. Simulated pressure-time histories: A_v = 3.4 m^2, Δ_g = 0.176 m, and h_{ig} indicated for peaks.

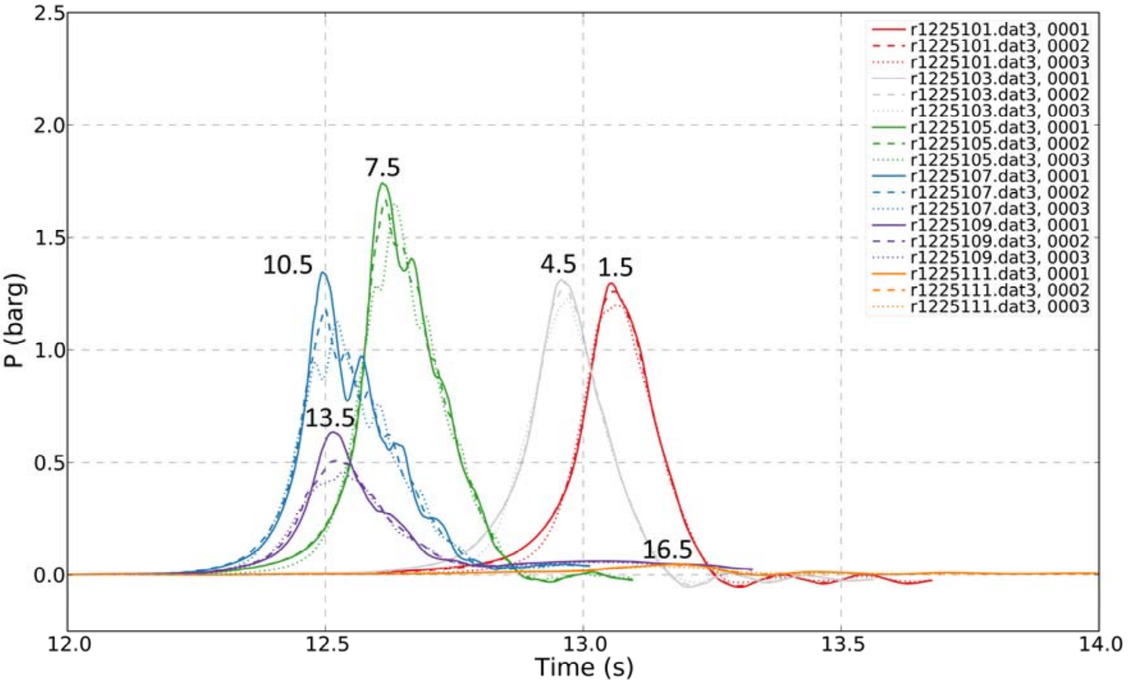

Fig. 8. Simulated pressure-time histories: A_v = 3.4 m^2, Δ_g = 0.264 m, and h_{ig} indicated for peaks.

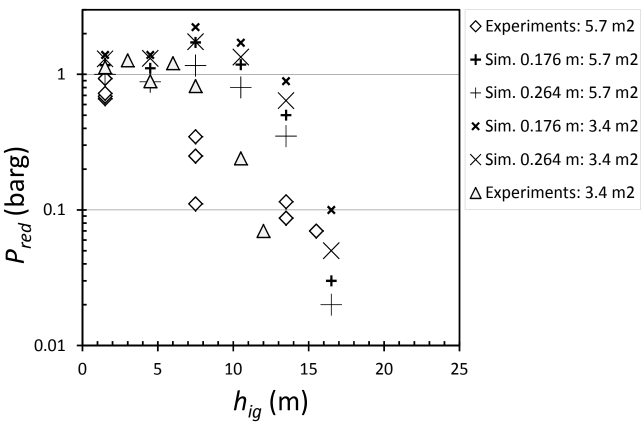

Fig. 9. Summary of results for the two grid resolutions.

Of particular concern with respect to dust explosion safety is the occurrence of singular tests that yield significantly higher explosion pressures than the remaining tests in a series [33, 49] – it may be a mere coincidence that these results are discovered. Large-scale explosions experiments are rarely repeated [50], and the inherent variation in the results from actually repeated tests represents a challenge with respect to the development of empirical correlations. To this end, the use of CFD simulations in conjunction with experimental results represents a valuable alternative towards improved understanding of the dust explosion phenomenon.

The overall trends for the reduced explosion pressure from the CFD simulations of the experiments in the 236-m^3 silo are in good agreement with observations, and confirm the observation that P_{red} is very sensitive to ignition location in long slender silos or other enclosures. The simulation results highlight the effect of dust distribution and turbulent flow conditions within the silo. Figures 5 and 6 show pressure-time histories characterised by strong pressure oscillations, with frequency in the range 4-7 Hz. Eckhoff and co-workers observed the same phenomenon in several of the experiments in the actual silo [34-35]. Future work will focus on more detailed modelling of multiphase flow and combustion, combined with more extensive parameter variation to explore the sensitivity of the model system.

CONCLUSIONS

A series of large-scale dust explosion experiments performed in a 236-m^3 silo has been simulated with the CFD tool DESC. Given the inherent uncertainty associated with large-scale dust explosion experiments, and the relatively simple model system [27], the results are satisfactory. However, there is still a need for improving the modelling of multiphase flow and heterogeneous combustion, and future improvements to the model system will no-doubt benefit from repeated large-scale experiments of high quality.

Current standards and guidelines for explosion protection are reasonably well developed, but there is still a need for improved methodologies, particularly for design of relatively complex geometries: grain elevators, pneumatic conveying systems, large silo complexes, etc. It is not obvious that this challenge can be met simply by introducing additional or improved empirical correlations in codes or standards:

> *"Ignorance* [of phenomena] *and a culpable negligence of those precautions which ought to be taken, have often caused more misfortune and loss than the most contriving malice: it is therefore of great importance that these facts should be universally known, that public utility may reap from them every possible advantage".*
>
> Count Carlo Ludovico Morozzo di Bianzè (1743-1804) [51]

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