

SIMULATING DUST EXPLOSIONS WITH THE FIRST VERSION OF DESC

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A new CFD-code for simulating dust explosions in complex geometries (DESC) is currently being developed by a consortium of 11 participants. The intention is to use experimental data from standardized tests as input to combustion models in the new code; the paper illustrates how this is done in the first versions of DESC. Uncertainties associated with the chosen approach are pointed out, and future challenges discussed. Application of the code is illustrated by simulating various explosion scenarios, using maize starch as model dust.

KEYWORDS: DESC, dust explosion, modelling

INTRODUCTION

Dust explosions represent a hazard to both personnel and equipment in industries that handle combustible powders. Primarily one seeks to reduce the risk posed by dust explosions by preventing them from taking place, either by eliminating all possible ignition sources, or by avoiding the formation of combustible dust clouds altogether. However, if the possibility of an explosion cannot be ruled out, measures for minimizing damage have to be considered. In some cases, the enclosure containing the combustible dust-air mixture can be made strong enough to withstand an internal explosion. In this case, only the maximum explosion pressure is needed as design parameter. More often, however, the enclosure will not be able to withstand the total explosion load, and other mitigating measures, such as venting, isolation and automatic suppression, must be implemented in the design.

Safe dimensioning of mitigating measures usually requires adequate knowledge about the burning rate of dust clouds in actual process situations. Traditionally, the reactivity of explosive dust clouds is characterized by the K_{st} value, defined as the rate of pressure rise determined in constant volume explosion vessels, multiplied by the cube root of the vessel volume. Bartknecht[1] presented experimental results that indicated that the so-called *cube–root-law* could be used to scale turbulent dust explosions between vessels with volumes larger than 40 litres. Results presented by Siwek[2,3] suggested that a 20-litre spherical vessel could produce K_{St} values that agree with data from the standardized 1-m^3 ISO-vessel[4]. However, the cube-root-law can only be regarded as a valid scaling relationship under hypothetical circumstances[5–8], such as: near spherical vessels, central point ignition, spherical propagation of a thin flame, the same mass burning rate in both vessels, etc. Several so-called *integral balance models*[8] have been introduced in order to overcome some of the limitations with the cube-root-law. Although such models are limited to relatively simple geometries, they may prove useful for estimating fundamental flame propagation parameters of combustible mixtures.

Although acceptable levels of risk usually can be achieved with design according to experience, empirical formulas, or existing guidelines; better prediction of flow, flame propagation and pressure build-up in complex geometries can be accomplished by *computational fluid dynamics* (CFD). Solutions based on CFD have much higher potential for being optimised with respect to risk/cost, especially for complex geometries, compared to simpler methods. It appears that the new ATEX directives have created a demand for a more differentiated approach to design of explosion mitigation systems in Europe; a properly validated CFD-code for dust explosions will be a most useful tool to meet this need. The code could be useful both with respect to risk assessments required by the *user directive*[9], and for verification of equipment according to the *products directive*[10]. In time, a CFD-code for dust explosions may be used to estimate the effect of mitigating measures such as explosion resistant equipment, venting, suppression and isolation; complementing guidelines given in the respective standards[11–14]. Similar CFD-codes for gas explosions are currently used by the petroleum industry as an integrated part in quantitative risk analysis[15].

One of the main challenges when developing a CFD-code for dust explosions will be to find appropriate combustion models for dust-air suspensions. This paper explores the possibility of using results from standardized tests in 20-litre explosion vessels as input to the combustion model in a new CFD-code called DESC (*dust explosion simulation code*).

THE DESC PROJECT

The main aim of the DESC project is to produce a CFD-code that can estimate the course of industrial dust explosions. The project is supported by the European Commission, and organized as a consortium with 11 participants: HSL, GexCon, TNO, Inburex, FSA, Fraunhofer-ICT, Øresund Safety Advisors, Hahn & Co, Lyckeby Culinar, and the Technical Universities of Delft and Warsaw. Contributions are also received from Fike, Ineris and University of Bergen.

The project was initiated early 2002; and includes extensive experimental work, measurements in real process plants, modelling and validation. Turbulent flow parameters and burning rates for dust clouds will be measured in various test vessels: 20-litre (TU Delft), 300-litre (HSL), 1-m^3 (Fike), 2-m^3 (HSL), and vertical ducts (Fraunhofer-ICT, Ineris). Explosion experiments in linked vessels will include both vented (HSL) and enclosed (TNO) systems, and quenching of dust flames propagating from one vessel to another (GexCon). Dispersion of dust layers by turbulent flow or shock waves will be investigated both experimentally and theoretically (TU Warsaw). Turbulence parameters and dust concentrations will be measured (Inburex, FSA and Øresund SA) in real process plants (Hahn & Co and Lyckeby Culinar). Combustion models for dust clouds will be developed (GexCon, TNO), and implemented in the CFD-tool (GexCon). Results produced by the new tool will be compared with current design methodologies and case histories (Inburex). The first commercial version of DESC is expected at the end of the project period, i.e. in 2005.

EXPERIMENTS

Experiments with two types of maize starch, *Meritena A* and *Maizena*, have been performed in a 20-litre explosion vessel of the USBM-type at the University of Bergen. Experimental procedures, and systems for dispersion, ignition and data acquisition, are almost the same as for the 20-litre Siwek sphere[16]. However, most tests were ignited by an electric arc with a total energy release of about 6 Joules and duration 3 milliseconds; further details are described elsewhere[17].

MODELLING

This section illustrates how experimental data for one dust, maize starch, are used to generate input for a combustion model. It should be emphasized that the approach described here represents the status at an early stage in the development of DESC, and that significant changes may take place as the testing and validation process proceeds.

THE FLACS-CODE

DESC will be based on the existing CFD-code for gas explosions called FLACS (FLame ACceleration Simulator). FLACS is a finite volume code where transport equations for mass, momentum, enthalpy, fuel, mixture fraction, turbulent kinetic energy (k) and turbulent energy dissipation rate (ε) are solved on a structured Cartesian grid. All solid objects are mapped to the grid using porosities, and sub-grid models are used to describe phenomena that cannot be resolved on the grid. The graphical user interface for FLACS includes the pre-processor CASD (Computer Aided Scenario Design) and the post-processor Flowvis. Scenarios, including geometry, grid, ignition, monitor points, output parameters, etc., are defined in CASD; results from simulations are presented in Flowvis. Previous work on dust explosions have been done with both FLACS[18–21] and DESC[22,23].

The combustion model currently used in FLACS is a so-called β flame model[24], where turbulent burning velocities (S_T) originates from a correlation by Bray[25]:

$$S_T = 0.875u'K^{-0.392} \tag{1}$$

where u' is the root mean square (rms) of the turbulent velocity fluctuations and K is the Karlovitz stretch factor. K can be expressed as[24]:

$$K = \frac{u'}{\lambda} \cdot \frac{\delta_f}{S_L} \approx \frac{u'}{\lambda} \cdot \frac{\alpha}{S_L^2} \tag{2}$$

where λ is the Taylor microscale for turbulence, δ_f is flame thickness, S_L is laminar burning velocity, and α is thermal diffusivity. Equation (1) originates from experimental data[26], and S_T [m/s] in FLACS is found from[24,27]:

$$S_T = \min \begin{cases} S_{T1} = 8 \cdot S_L^{0.284} \cdot u'^{0.912} \cdot \ell_m^{0.196} + S_L \\ S_{T2} = 15 \cdot S_L^{0.784} \cdot u'^{0.412} \cdot \ell_m^{0.196} \\ S_{T3} = 110 \cdot S_L^{1.33} \cdot \ell_m^{0.33} \end{cases} \quad (3)$$

where S_{T1}, S_{T2} and S_{T3} are used for low, medium and high turbulence levels, respectively; $\ell_m = C_\mu^{0.75} \cdot k^{1.5} \cdot \varepsilon^{-1}$ is a mixing length scale derived from the k–ε model[28] ($C_\mu = 0.09$ is a model constant). Correlations[24] are introduced for pressure, temperature, high strain rates, flame folding, etc. The turbulent length scale LT used by FLACS is defined as $LT = C_\mu \cdot k^{3/2} \cdot \varepsilon^{-1} = C_\mu^{0.25} \cdot \ell_m$.

MODELLING IN DESC

In the first version of DESC, dust clouds are modelled as a dense gas, i.e. a gas with very high molecular weight. Phenomena such as dispersion of dust layers by turbulent flow or shock waves, and dust particles settling out of dispersion due to gravity, cannot be modelled properly. Hence, use of the code is limited to primary dust explosions. In later versions of DESC, dust will be represented as a finite number of particle classes, and conservation equations will be solved for each class. In time, the code may include models for particle settling and redispersion of dust layers; hence, it could be possible to simulate secondary dust explosions.

Thermodynamic calculations for dust explosions are complicated by the fact that combustion processes in dust explosions rarely are complete. Hence, parameters such as *stoichiometric concentration, adiabatic flame temperature* and *constant volume explosion pressure* are of limited use[29]. The approach chosen for the first versions of DESC is to estimate the fraction of dust that reacts from heats of combustion and experimentally determined explosion pressures. It is assumed that the reactants have known chemical composition, e.g. $(C_6H_{10}O_5)_n$ for maize starch, and that product composition can be estimated by simplified chemical equilibrium calculations[24]. There are several uncertainties associated with this approach, e.g.:

- The measured explosion pressure for organic dusts such as maize starch may depend on the level of turbulence. This could be due to (i) reduced heat loss to the vessel walls at higher burning velocities[30], (ii) changes in composition in the pre-heat zone due to liberation of volatiles[28,31], and (iii) reduced real dust concentration because dust particles may settle out of suspension or adhere to solid surfaces[6].
- Maximum explosion pressure may occur for different dust concentrations in vessels of different scale[2]; this effect appears to depend on both type of dust and type/strength of ignition source.

Modelling volatiles liberated from various particle classes in the preheat zone of the flames may be necessary to solve some of these problems in later versions of DESC.

Turbulent burning velocities will be estimated by correlations such as (1). This approach was suggested by Bradley *et al.*[6], who found that the correlation of S_T/S_L with u'/S_L and K is similar for maize starch/air and gaseous fuel/air mixtures. However, such correlations require estimates for the laminar burning velocity of dust clouds. Such measurements have proven to be rather difficult to perform, and there is considerable scatter in published results[29,32,33]. Although it may be possible to get reliable estimates for laminar burning velocities for dust clouds, it is important to keep in mind that a dust cloud is a *mechanical suspension*, i.e. a system of fine particles dispersed by agitation; thus, dust flames are rarely laminar. The approach that is attempted used for this version of DESC involves the following three steps:

- A thin-flame model is used to estimate turbulent burning velocities from measured rates of pressure rise in standardized tests (t_{ip} and p_{ip} defines the inflection point where $(dp/dt)_m$ is measured; p_i and p_f is initial and final absolute pressures; V_v and r_v is volume and radius of the explosion vessel):

$$S_{T,ip} = \frac{1}{3(p_f - p_i)}\left(\frac{dp}{dt}\right)_m \underbrace{\left(\frac{3V_v}{4\pi}\right)^{1/3}}_{r_v} \left(\frac{p_{ip}}{p_i}\right)^{-1/\gamma} \times \left\{1 - \left(\frac{p_f - p_{ip}}{p_f - p_i}\right)\left(\frac{p_{ip}}{p_i}\right)^{-1/\gamma}\right\}^{-2/3} \qquad (4)$$

- $LT_{ip} = LT(t_{ip})$ and $u'_{ip} = u'(t_{ip})$ are assumed to have certain values at t_{ip}. LT_{ip} is assumed to be of the order 6 millimetres, based on simulations; u'_{ip} is estimated from an empirical equation[8] for decay of turbulence in a 20-litre sphere fitted with a rebound nozzle ($u'_0 = 3.75\,\mathrm{m/s}$, $t_0 = 60$ milliseconds and $n = -1.61$):

$$\frac{u'_{ip}}{u'_0} = \left(\frac{t_{ip}}{t_0}\right)^n \qquad 60\,\mathrm{ms} < t_{ip} < 200\,\mathrm{ms} \qquad (5)$$

- Laminar burning velocities are estimated with an inverse version of equation (3):

$$S_L = \max\begin{cases} S_{L1} = 0.0316 \cdot S_{T,ip}^{1.276} \cdot LT_{ip}^{-0.25} \cdot u'^{-0.526}_{ip} \\ S_{L2} = 0.0294 \cdot S_{T,ip}^{0.75} \cdot LT_{ip}^{-0.25} \end{cases} \qquad (6)$$

The expression for S_{L2} is used for high strain rates.

The method described above was applied to the experimental data for maize starch shown in Figure 1; the resulting estimated laminar burning velocities are shown in Figure 2. Laminar burning velocities and fractions of fuel that is allowed to react (λ),

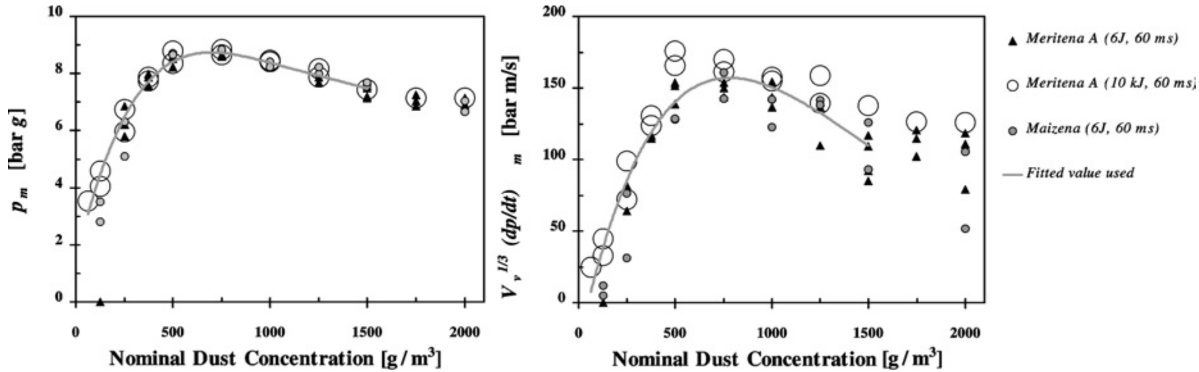

Figure 1. Corrected explosion pressure (left) and volume corrected rate of pressure rise (right) for maize starch. Two different types of dried maize starch are used, and both tests ignited by chemical igniters (two 5 kJ igniters) and tests ignited by an electric arc are shown. Fitted lines represent the 'average' values used as input to DESC

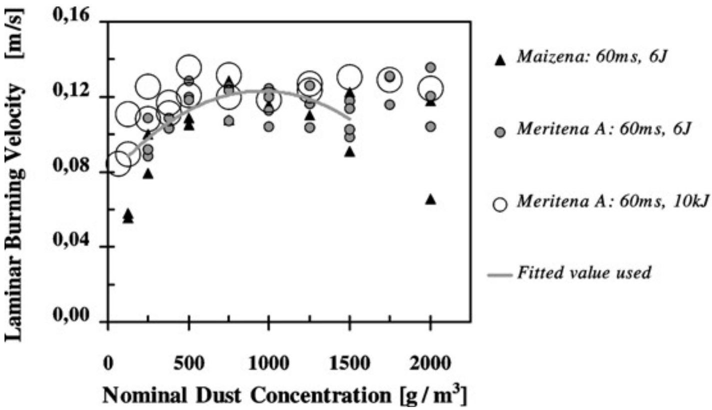

Figure 2. Estimated laminar burning velocities generated from the data in Figure 1

used as input to DESC, are shown in Figure 3. Dust concentrations higher than 1500 g/m^3 were not included in the final model because nominal and real dust concentrations were thought to be significantly different for such high dust loading. There are significant uncertainties associated with the chosen approach, including:

- The concept of *burning velocity* requires a well-defined flame zone, and estimates derived from pressure-time measurements in closed vessels may deviate significantly from the

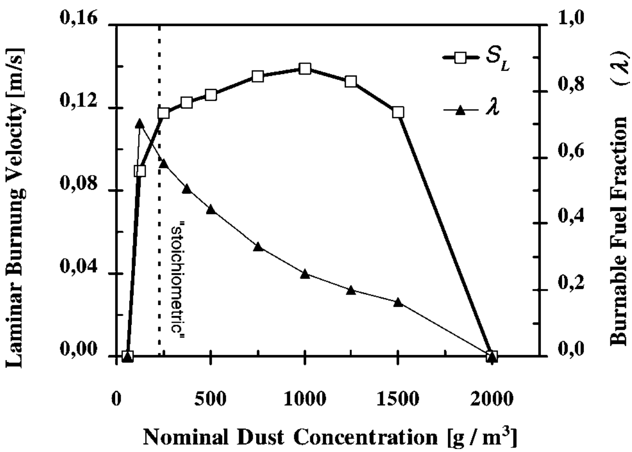

Figure 3. Laminar burning velocity and fraction of burnable fuel used as input to DESC. Lower explosion limit is set to 60 g/m^3; upper is somewhat arbitrarily chosen to 2000 g/m^3

real flame front velocities due to volumetric combustion[34]. Three-zone models indicate that significant deviations from the thin flame model can be expected if the relative flame thickness (δ_f/r_v) exceeds one per cent[7]. Measured flame thickness for 300–400 g/m^3 cornstarch/air mixtures are of the order 0.1 and 0.2 m, for $u' = 1.5$ and $u' = 3.3$ m/s respectively[35]; i.e. of the same order as the radius of the 20-litre vessel.

- The values for both u'_0 and n in (5) may be questioned, for several reasons. First, there seems to be no generally accepted smoothing procedure that can be used to 'define' the average velocity $\bar{u}$ needed for estimating u' from measured LDA-data in transient flow fields. Second, the influence of dispersed particles on turbulence, or *turbulence modification*, is not straightforward to estimate, especially for high dust loading. Third, it is assumed that the decay of turbulence is unaffected by the explosion; this is not obvious.
- Since the turbulent energy spectrum evolves in time as the turbulent energy decays, the turbulent length scale is not constant[36]. This, and the fact that turbulent length scales are inherently difficult to measure during the transient dispersion process in 20-litre vessels, makes it very difficult to estimate *LT*.
- The constants in equation (3), and hence (6), may have to be changed, going from gaseous to solid fuels; also, they may differ for different dusts.
- A further complication is the fact that the explosible concentration range for dust suspensions is much wider than for gaseous mixtures; it has been suggested that the flame proceeds through paths provided by small particles, while largely bypassing the large ones[37]. While reasonably accurate values for the lower explosion limit usually can be determined in standardized tests, the upper limit has proven inherently difficult to estimate[38,39].

Nevertheless, the described approach will be attempted used for various types of dust in the first version of DESC. In this work, the model resulting from the experimental data for maize starch, shown in Figure 1, has been used for all simulations.

OTHER FEATURES PLANNED FOR FUTURE VERSIONS OF DESC

Ideally, DESC should be able to model the effect of most kinds of mitigation devices used in industry. Vent panels are already modelled; suppression and isolation of explosions will be included in the near future. Dust lifting and dust settling will also be modelled, provided suitable subgrid models can be found. In the future, there should also be other solutions for the grid (e.g. unstructured grid[40]) since the overall system in which the flame propagates can be rather complicated to represent on the currently used Cartesian grid.

SIMULATIONS

This section explores some possible applications of a CFD-code for dust explosions, using the maize starch model described in 4.2 to simulate explosion scenarios taken from published experimental work. Although the chosen examples are relatively simple compared to conditions found in industry, they nevertheless illustrate that the code is able to reproduce trends and phenomena seen in the experiments.

EXPLOSIONS IN VENTED VESSELS

DESC should be able to estimate the influence of parameters such as shape of enclosure, dust concentration (c_d), flow conditions, initial pressure and temperature, vent area (A_v), static activation pressure for vents (p_{stat}), position of vents, vent ducts, position of ignition, etc., on the maximum reduced explosion overpressure ($p_{red,max}$) generated inside an enclosure by dust explosions. Hence, the code could be a useful tool when designing process plants. The dust dispersion and explosion experiments simulated in this section are described in detail by Hauert *et al.*[41,42].

Experiments

Dust concentration, velocity and rms turbulence velocity were measured at several positions in a 12-m^3 cylindrical silo ($D = 1.6$ m, $L/D = 3$). Various methods were used to generate dust clouds; ring nozzles and pressurized dust reservoirs ('homogeneous cloud'), mechanical feeding, pneumatic dust injection tangentially, and pneumatic dust injection vertically downward. The pneumatic conveying velocity (u_c) was to set either 15 m/s, or to a maximum value of about 22–25 m/s. The conveying pipe had an inner diameter of 75 mm, and dust concentrations in the pipe could be varied (feeding rates $\xi = 1$, 3, 5 or 7 kg/m^3). One example of measured velocity and rms turbulence velocity (z-components, vertical filling, $\xi = 3$ kg/m^3) is shown in Figure 4.

For explosion tests, the silo bottom was filled with sand; the silo volume was then reduced to 9.4 m^3. The following vent areas were used: 0.15, 0.3, 0.5 and 0.7 m^2, the silo was vented with polyethylene film ($p_{stat} = 0.1$ bar). Chemical igniters (10 kJ), located at levels 0.75, 2.60 or 3.75 m, were used as ignition source. For explosion tests with pneumatic injection, air was injected for 30 s, before a rotary air lock fed dust (maize starch: $K_{st} = 140$ bar m/s, $p_{max} = 9$ bar) into the line for another 30 s; ignition was triggered during dust injection. Exhaust air was let out through an outlet (∅75 mm) at the silo top. Some experimental results for explosions are plotted in Figure 5; vertical dust injection, $\xi = 3$ and 5 kg/m^3.

Simulations

A vertical cross-section of the simulated representation of the silo is shown in Figure 4, together with a top view illustrating the four vent openings; note that this figure shows the coordinate system used in the simulations. Cubical grid cells of 0.1 m was used, and three monitor points, $M1$–$M3$, are located at $z = 0.75$, 1.75 and 4.75 m. By setting the activation pressures for the four vent panels ($P1$–$P4$ in Figure 4) to either 0.1 bar*g*, or to a value much higher than p_{max}, the total vent area in the simulations could be set to 0.15, 0.3, 0.5 or 0.7 m^2. Only vertical pneumatic filling have been simulated ($\xi = 5$ kg/m^3, $u_c = 23$ m/s). Because dust settling could not be modelled, the duration of the dispersion process was reduced to get average dust concentrations comparable to those measured in the experiments. Simulated velocities (z-components), rms turbulent velocities and dust concentrations after 9 seconds of dust dispersion are illustrated in Figure 6; explosion simulations were started from these initial conditions for all vent

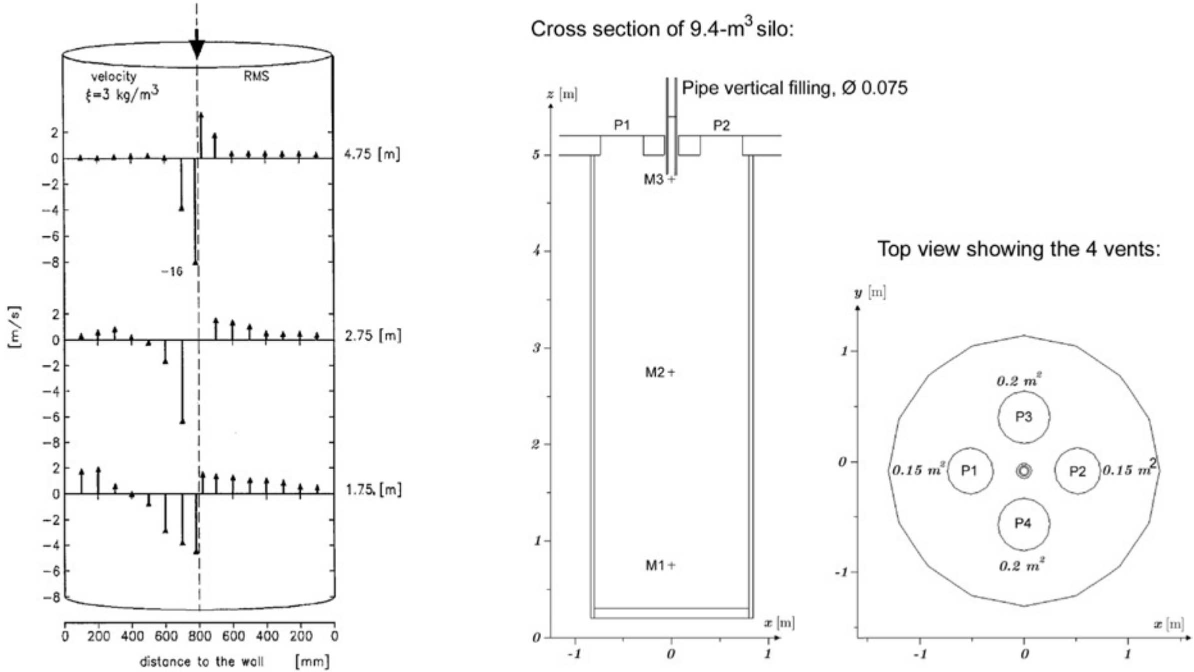

Figure 4. Measured vertical velocity and rms turbulence velocity for vertical filling ($\xi = 3\ \mathrm{kg/m^3}$) of 12-m^3 silo (right; from Hauert *et al.*[42]); vertical cross-section and top view of simulated 9.4-m^3 silo (left)

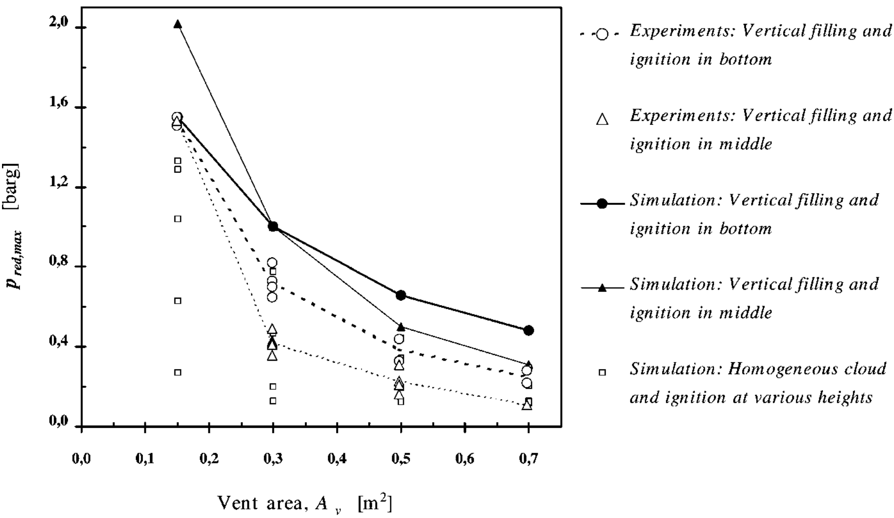

Figure 5. Simulated and experimental maximum reduced explosion pressures in a 9.4-m^3 silo as function of vent area for various ignition positions; experimental values from Hauert *et al.*[42]. Vertical filling: $\xi = 3$ or $5\ \text{kg/m}^3$ in experiments, $5\ \text{kg/m}^3$ simulated; $u_c = 22\text{–}25\ \text{m/s}$ in experiments, 23 m/s simulated. Initial conditions for simulated homogeneous dust cloud: $x_{ig} = y_{ig} = 0$; $z_{ig} = 0.75$, 1.75, 2.75, 3.75 or 4.75 m; $c_d = 200\ \text{g/m}^3$; $u' = 2.1\ \text{m/s}$; $LT = 0.05$ m

areas, with ignition either in the bottom or in the middle of the silo ($z_{ig} = 0.75$ or 2.75 m). Some explosion simulations are illustrated in Figure 7, and the simulated reduced explosion pressures are plotted in Figure 5. Results from explosion simulations with homogeneous dust clouds, ignited at five different positions, are also shown in Figure 5. The two lowest ignition positions resulted in the highest pressures, when igniting closer to the silo top (vent), pressures decreased rapidly.

Discussion

Simulated vertical velocities, and rms turbulent velocities, shown in Figure 6, are in relatively good agreement with experimental values, Figure 4. The difference in distribution of dust concentrations is more pronounced, as would be expected with a 'dense gas' representation of the dust cloud. Simulated maximum reduced explosion pressures are generally higher than experimental values; however, general trends seem to be reproduced fairly well. For large vent areas, ignition in the middle of the silo results in lower pressures than bottom ignition; however, the opposite seems to be the case for smaller vent areas. This is suggested both by simulated results, and by extrapolating

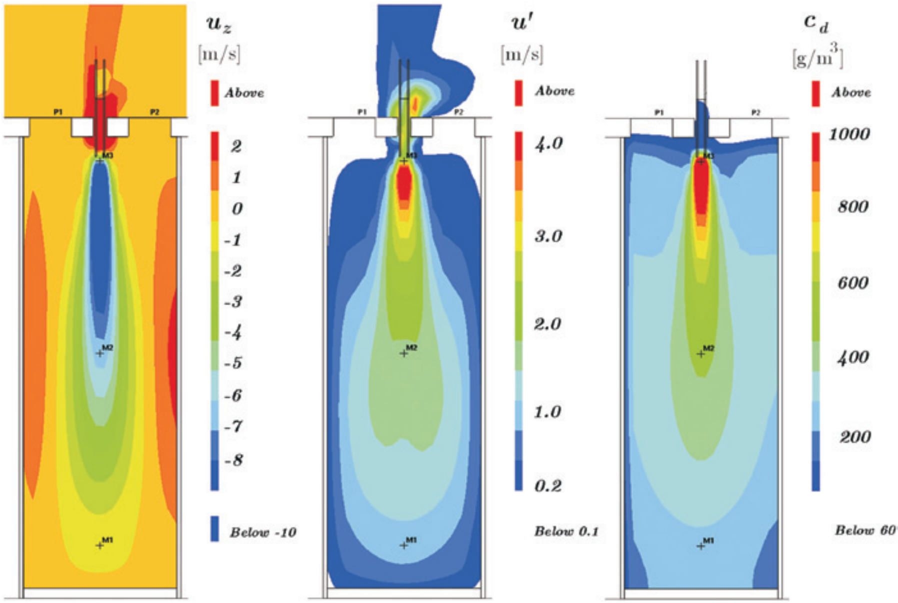

Figure 6. Simulated vertical velocity component (left), rms turbulence velocity (middle), and dust concentration (right) in 9.4-m^3 silo 9 seconds after onset of dispersion process.

experimental results to vent areas smaller than 0.15 m^2. This phenomenon can perhaps be explained by delayed outflow due to high flow resistance for smaller vents, giving centrally ignited flames more time to propagate downward (following the flow) at the high levels of turbulence found in the central part of the silo; this scenario is illustrated in Figure 7.

INTERCONNECTED VESSEL SYSTEMS

During normal operation, dust clouds within the explosible concentration range are most likely to occur inside process equipment. Since a typical industrial powder handling process usually involves several interconnected units, an explosion in one part of the plant may compress an unburned explosible dust cloud in another interconnected part. If the pre-compressed cloud is ignited, very high pressures may occur if there is insufficient venting of the enclosure. This phenomenon is called *pressure-piling*, and a CFD-code for dust explosions should be able to describe it. Experimental dust explosions in totally enclosed interconnected vessel systems, similar to the scenarios simulated in this section, are described by Lunn *et al.*[43].

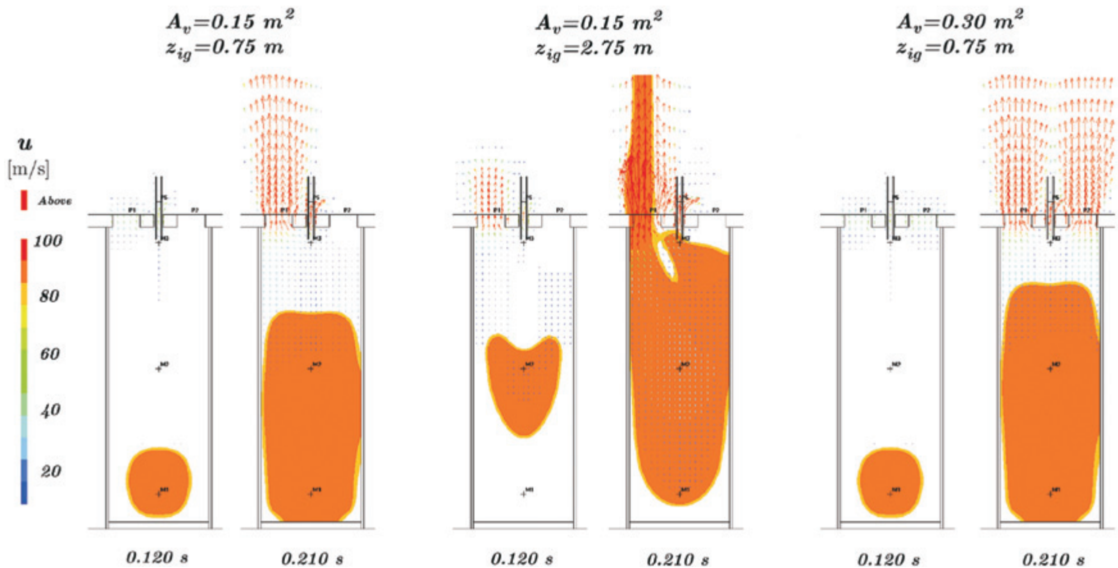

Figure 7. Simulated flame development (represented as combustion products) and velocity fields for various ignition positions (z_{ig}) and vent areas (A_v); two time steps are shown for each scenario, time relative to ignition after 9 s of dust dispersion. Simulated maximum reduced explosion pressures for the three scenarios are (from left to right): 1.6, 2.0 and 1.0 bar*g*

Experiments
Lunn *et al.*[43] investigated explosions of coal dust and toner for various configurations of linked vessels. Vessels with volume 2, 4, and 20-m^3 were used; two vessels were connected by a 5 m pipe, ∅0.15, 0.25 or 0.50 m. Dust was injected from pressurized reservoirs, and pressures were measured in both vessels, see Figure 8.

Simulations
Only a configuration of two vessels, 4 and 20 m^3, connected by a 5 m long ∅0.25 pipe, has been simulated, see Figure 8; the 0.08 m cubical grid cells can be seen in parts of the simulation volume that are totally blocked. Three monitor points are shown; simulated pressure in the 4-m^3 vessel will be referred to as $P1$, in the 20-m^3 as $P2$ (no significant pressure difference between positions $M2$ and $M3$). Since data for dust concentrations, reservoir volumes and ignition delay times were unknown, and in the absence of experimental input to DESC for the dusts used in the experiments, a homogeneous cloud of maize starch was chosen as initial condition for the simulations ($c_d = 500$ g/m^3, $u' = 1.2$ m/s, $LT = 0.05$ m). Three different ignition positions were tested; the resulting pressure-time traces are shown in Figure 9, together with simulated flame developments 0.18 s after ignition.

Discussion
Although direct comparison with experimental results is not possible in this case, several important phenomena observed in the experiments seem to be reproduced in the simulations. The results illustrate the importance of ignition position in determining the course of explosions in interconnected vessel systems. With ignition in the far end of the 20-m^3 vessel, flame arrival in the 4-m^3 vessel is enough delayed for pressure-piling to take place; the simulated pressure-time curve in Figure 9 has much in common with experimental results for a similar scenario, shown in Figure 8.

CONCLUSIONS

Experimental results for maize starch obtained in a 20-litre explosion vessel have been used as input for the combustion model in the first version of DESC. Although the modelling work is still in an early phase, simulations of various dust explosion scenarios seem to reproduce trends and phenomena found in experiments rather well. It can also be expected that increased understanding of the dust explosion phenomenon will be gained through the systematic validation work planned for the new CFD-code. A major factor determining the success, or lack of success, of a CFD-code for dust explosions, will be how well suited results from standardized tests in 20-litre explosion vessel are in revealing the fundamental combustion characteristics of dust clouds. Although the transient nature of these tests makes it particularly challenging to extract quantitative information on the inherently complex phenomena involved in particle-laden flow and heterogeneous combustion, the results so far are encouraging.

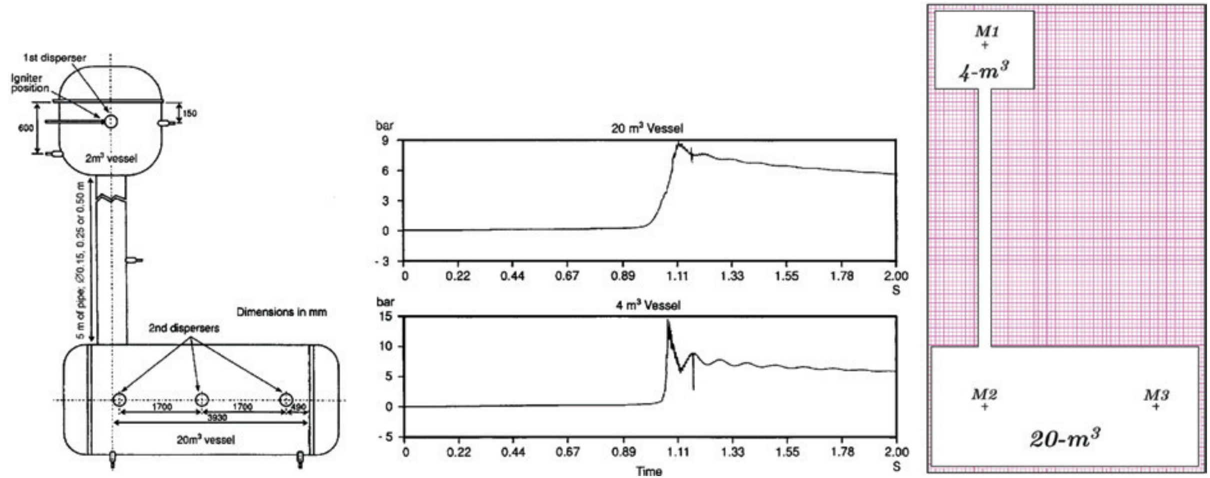

Figure 8. Interconnected vessel system, consisting of a 2-m^3 vessel connected to a 20-m^3 vessel, from Lunn *et al.*[43] (left). Pressure-time traces for coal dust explosion ignited in a 20-m^3 vessel connected to a 4-m^3 vessel by a 5 m long Ø0.25 m pipe, from Lunn *et al.*[43] (middle). Cross-section of the interconnected vessel system simulated in this work (right)

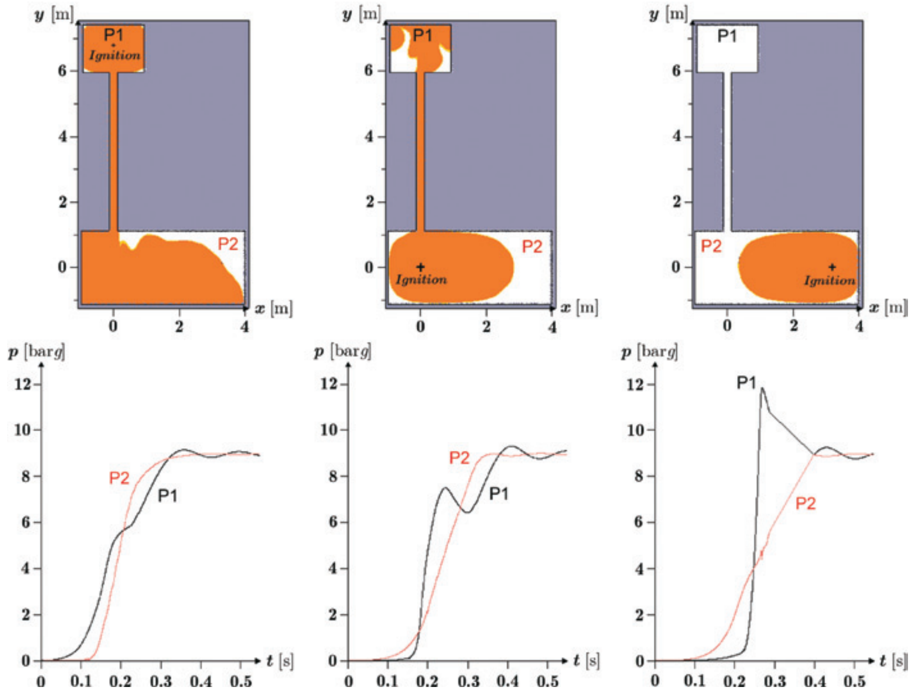

Figure 9. Simulated flame development, 0.18 s after ignition, in three different positions, for 500 g/m^3 maize starch explosions in a totally enclosed interconnected vessel system; the corresponding simulated pressure-time histories for the explosions are shown below

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the European Commission for financial support to the DESC project; acknowledgements are also due to Dr. Frank Hauert (BGN) and Mr. Paul Holbrow (HSL) for permissions to reproduce figures.

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