IChemE
www.icheme.org/journals
doi:10.1205/psep.04237

0957–5820/05/$30.00+0.00

Trans IChemE, Part B, March 2005
Process Safety and Environmental Protection, 83(B2): 151–160

SIMULATING DUST EXPLOSIONS WITH THE FIRST VERSION OF DESC

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DESC is a new CFD-code that is being developed for simulating dust explosions in complex geometries. In the methodology followed, dust–air mixtures are ignited to deflagration in laboratory test vessels to provide information on fundamental flame propagation parameters. These quantities are subsequently used as input for combustion models in the CFD-code. Experiments were performed with maize starch in a 20-litre explosion vessel, the laminar burning velocity was extracted from the experimental pressure–time curve, and subsequently used to predict what might happen if the same mixtures would explode in larger geometries, namely, a vented silo, and, a system involving two interconnected vessels. The results presented in this paper are preliminary and serve as a proof of principle. Uncertainties and gaps in knowledge are identified in the light of this approach, and future challenges discussed.

Keywords: DESC; dust explosion; modelling.

INTRODUCTION

Dust explosions represent a hazard to both personnel and equipment in industries that handles 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 mitigatory 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 maximum rate of pressure rise determined in constant volume explosion vessels, multiplied by the cube root of the vessel volume. Bartknecht (1971) 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 (1977, 1988) suggested that a 20-litre spherical vessel could produce K_{St} values that agree with data from the standardized 1-m^3 ISO-vessel (ISO, 1985). However, the cube-root-law can only be regarded as a valid scaling relationship under hypothetical circumstances (Eckhoff, 1984; Bradley *et al.*, 1988; Dahoe *et al.*, 1996, 2001a), such as: near spherical vessels, central point ignition, spherical propagation of a thin flame, the same mass burning rate in both vessels, and so on. Several so-called integral balance models have been introduced in order to overcome some of the limitations with the cube-root-law (Dahoe *et al.*, 2001a). 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 (ATEX 1999/92/EC, 1999), and for

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verification of equipment according to the products directive (ATEX 94/9/EC, 1994). 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 (prEN14460, 2002; prEN14491, 2002; prEN14373, 2002; prEN15089, 2004). Similar CFD-codes for gas explosions are currently used by the petroleum industry as an integrated part in quantitative risk analysis (NORSOK Z-013, 2001).

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 Advisers, 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), 2 and 10-m^3 (Fike), 2-m^3 (HSL), and vertical ducts (Fraunhofer-ICT and 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 (Cesana and Siwek, 2001). 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 (Skjold, 2003). Experimental results are summarized in Figure 1.

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

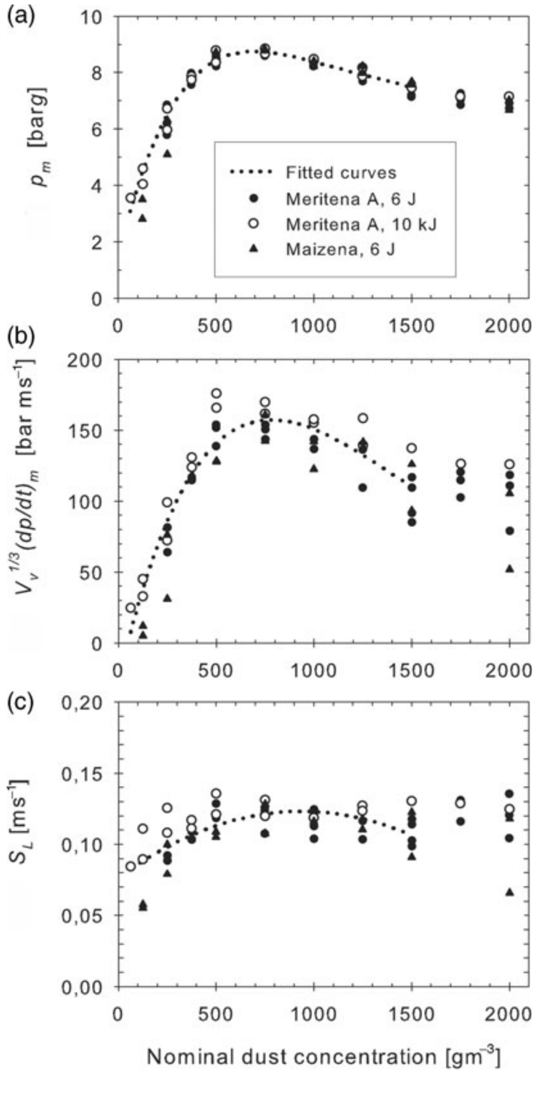

Figure 1. Experimental results for maize starch; two different types of dried maize starch are used, and both tests ignited by two 5 kJ chemical igniters, and tests ignited by a 6 J electric arc, are shown: *(a)* corrected explosion pressure, *(b)* size-normalized rate of pressure rise and *(c)* estimated laminar burning velocities.

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, and so on, are defined in CASD; results from simulations are presented in Flowvis. Previous work on dust explosion simulation has been presented for both FLACS (van Wingerden, 1996; van Wingerden *et al.*, 2001; Arntzen *et al.*, 2003; Siwek *et al.*, 2004) and DESC (Hansen *et al.*, 2004; Skjold *et al.*, 2004).

The combustion model currently used in FLACS is the so-called β flame model (Arntzen, 1998), where turbulent burning velocities (S_T) originates from a correlation by Bray (1990):

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

where u' is the root mean square (rms) of the turbulent velocity fluctuations and Ka is the Karlovitz stretch factor. Ka can be expressed as (Arntzen, 1998)

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

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 (Abdel-Gayed *et al.*, 1987), and S_T (m s^{-1}) in FLACS is found from the equation system (Popat *et al.*, 1996; Arntzen, 1998):

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

where S_{T1}, S_{T2} and S_{T3} are used for low, medium and high turbulence levels, respectively. The mixing length scale ℓ_m is defined as $\ell_m = C_\mu^{0.75} \cdot k^{1.5} \cdot \varepsilon^{-1}$, where the model constant $C_\mu = 0.09$ is derived from the k–ε model (Lauder and Spalding, 1974). Notice that, unlike the correlation proposed by Bray (1990) in equation (1), the first expression in equation (3) implies that the turbulent burning velocity reduces to the laminar burning velocity in the absence of turbulence. Further correlations are then introduced for pressure, temperature, high strain rates, flame folding, and so on (Arntzen, 1998). The turbulent length scale LT used by FLACS is defined as $LT = C_\mu \cdot k^{3/2} \cdot \varepsilon^{-1} = C_\mu^{0.25} \cdot \ell_m$.

The correlations in system (3) deserve some further clarification. A general set of equations for the turbulent burning velocity, S_T, and the turbulent flame thickness, δ_T, was derived by Dahoe (2000). The Dahoe equations for turbulent flame propagation are:

$$\frac{S_T}{S_L} = 1 + \left(\frac{\ell_m/u'}{\delta_L/S_L}\right)^{a'} \left(\frac{u'}{S_L}\right)^{b'} = 1 + Da^{a'} \left(\frac{u'}{S_L}\right)^{b'} \tag{4}$$

and

$$\frac{\delta_T}{\delta_L} = 1 + \left(\frac{\ell_m/u'}{\delta_L/S_L}\right)^{a'} \left(\frac{\ell_m}{\delta_L}\right)^{b'} = 1 + Da^{a'} \left(\frac{\ell_m}{\delta_L}\right)^{b'} \tag{5}$$

where δ_T and δ_L denotes turbulent and laminar flame thickness, respectively, and Da the Damköhler number. It was argued in a later contribution (Dahoe *et al.*, 2001b) that $a' = a'' = 0.25$, b' assumes values between 0.5 and 1.0, and b'' assumes values between 1.6 and 2.0. Equations (4) and (5) can be used in conjunction with the Dahoe equations for laminar flame propagation (Dahoe, 2000; Dahoe and de Goey, 2003), resulting in a conjecture containing only two degrees of freedom, namely, the laminar burning velocity and the laminar flame thickness at reference pressure and temperature. If the first expression in system (3) is restated as:

$$\begin{aligned} \frac{S_T}{S_L} &= 1 + 8u'^{0.196}\delta_L^{0.196} \left(\frac{\ell_m/u'}{\delta_L/S_L}\right)^{0.196} \left(\frac{u'}{S_L}\right)^{0.912} \\ &= 1 + 8u'^{0.196}\delta_L^{0.196} Da^{0.196} \left(\frac{u'}{S_L}\right)^{0.912} \end{aligned} \tag{6}$$

its resemblance with equation (4) becomes evident, but it is also seen that the second term of the right-hand side is preceded by a multiplicative factor containing the turbulence velocity scale and the laminar flame thickness. This discrepancy results from the absence of the laminar flame thickness in system (3). In spite of this, the first correlation of system (3) is considered appropriate because the values of a' and b' (0.196 and 0.912) are seen to fall within the ranges argued by Dahoe. The second and third expression in system (3) cannot be restated in a similar form and need to be reconsidered at a later stage.

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. Hence, 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, and 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 the future, the code may include models for particle settling and redispersion of dust layers; hence, it could also be possible to simulate secondary dust explosions.

Thermodynamic calculations for dust explosions are complicated by the fact that combustion processes in dust explosions rarely goes to completion. Hence, parameters such as stoichiometric concentration, adiabatic flame temperature and constant volume explosion pressure are of limited use (Lee, 1988). 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 (Arntzen, 1998). There are several uncertainties associated with this approach. First, the measured explosion pressure for organic dusts such as maize starch may depend on the level of turbulence. This could be due to (1) reduced heat loss to the vessel walls at higher burning velocities (Kauffman *et al.*, 1984); (2) changes in composition in the pre-heat zone due to liberation of volatiles (Lee, 1988; Dahoe *et al.*, 2001b); and (3) reduced real dust concentration as a consequence of dust particles settling out of suspension or adhering to solid surfaces (Bradley *et al.*, 1988). Second, measured maximum explosion pressures may occur for different dust concentrations in vessels of different size (Siwek, 1977); this effect appears to depend on both type of dust and type/strength of ignition source. Modelling liberation of volatiles from various particle classes in the preheat zone of the flame may be one way of approaching these problems in later versions of DESC.

Turbulent burning velocities will be estimated by correlations such as equation (1). This approach was suggested by Bradley *et al.* (1988), who demonstrated that the correlation of S_T/S_L with u'/S_L and Ka is similar for maize starch/air and gaseous fuel/air mixtures. However, such correlations require estimates of the laminar burning velocity of dust clouds. Such measurements have proven rather difficult to perform, and there is considerable scatter in published results (Lee, 1988; Krause and Kasch, 2000; Dahoe *et al.*, 2002). It was pointed out by Dahoe *et al.* that this scatter arises from the lack of compensation for buoyancy effects and the effect of flame curvature on the laminar burning velocity, and the authors demonstrated the possibility of getting better estimates from direct measurements involving stabilized powder–air flames. 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. With this picture in mind, the approach followed in the present version of DESC (1.0b2) consists of the following three steps: (1) An estimate of the turbulent burning velocity is sought from measured rates of pressure rise obtained from standardized tests following the approach by Senecal and Beaulieu (1998). These authors extract the burning velocity from the experimental pressure–time curve by substituting the pressure measured in the inflection point of the pressure–time curve into the following equation by Dahoe *et al.* (1996):

$$S_{T,ip} = \frac{1}{3(p_f - p_i)} \left(\frac{dp}{dt}\right)_m \underbrace{\left(\frac{3V_v}{4\pi}\right)^{1/3}}_{r_v} \left(\frac{p_{ip}}{p_i}\right)^{-1/\gamma} \left\{1 - \left(\frac{p_f - p_{ip}}{p_f - p_i}\right)\left(\frac{p_{ip}}{p_i}\right)^{-1/\gamma}\right\}^{-2/3} \tag{7}$$

where t_{ip} and p_{ip} defines the inflection point of the pressure–time curve, i.e., the point where $(dp/dt)_m$ is measured; p_i and p_f is initial and final absolute pressures; V_v and r_v, respectively denote the volume and radius of the explosion vessel. (2) The turbulence parameters LT and u' are assumed to have certain values at time t_{ip}. The length scale (LT_{ip}) is assumed to be of the order 6 mm, based on simulations. The rms turbulent velocity (u'_{ip}) is estimated from the decay law of turbulence for the transient flow in a 20-litre sphere equipped with a rebound nozzle, as observed by Dahoe *et al.* (2001a):

$$\frac{u'_{ip}}{u'_0} = \left(\frac{t_{ip}}{t_0}\right) \quad 60\,\mathrm{ms} < t_{ip} < 200\,\mathrm{ms} \tag{8}$$

with the constants $u'_0 = 3.75\ \mathrm{m\,s^{-1}}$, $t_0 = 60\ \mathrm{ms}$ and $n = -1.61$. (3) Laminar burning velocities are estimated with an inverse version of system (3):

$$S_L = \max\begin{cases} S_{L1} = 0.0316 \cdot S_{T,ip}^{1.276} \cdot LT_{ip}^{-0.25} \cdot u'^{-0.526}_{ip} \\ S_{L2} = 0.0294 \cdot S_{T,ip}^{0.75} \cdot LT_{ip}^{-0.25} \end{cases} \tag{9}$$

where 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 Figures 1a and 1b; the resulting estimated laminar burning velocities are shown in Figure 1c. The effect of chemical igniters is most pronounced for low dust concentrations, and there is significant scatter in the results for high dust concentrations. The input to DESC, i.e., laminar burning velocities and fractions of burnable fuel (λ), is shown in Figure 2. Experimentally determined burning velocities for dust concentrations higher than $1500\ \mathrm{g\,m^{-3}}$ were not included in the final model because nominal and real dust concentrations were thought to be significantly different for such high dust loading. Since the combustion model in DESC requires the range of combustible dust concentrations to be specified, the curves in Figure 2 are terminated at certain lower and upper dust concentration limits. From the experimental results in Figure 1, the lower explosion limit was

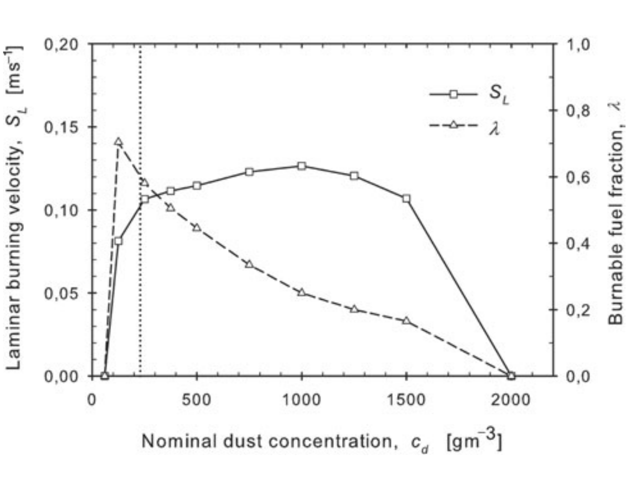

Figure 2. Laminar burning velocity, and fraction of burnable fuel, that is used as input to DESC. Lower explosion limit estimated to $60\ \mathrm{g\,m^{-3}}$; upper explosion limit set to $2000\ \mathrm{g\,m^{-3}}$.

estimated to be 60 g m^{-3}, which seems to be a typical value for maize starch according to Beck *et al.* (1997). Since almost all dust concentrations encountered in this work was below 1000 g m^{-3}, the upper limit was somewhat arbitrary set to 2000 g m^{-3}, although the real upper explosion limit for maize starch may be significantly higher. 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 real flame front velocities due to volumetric combustion (Lee *et al.*, 1987). Work on 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 1% (Dahoe *et al.*, 1996). According to Tai *et al.* (1988), 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^{-1}, respectively; i.e., of the same order as the radius of the 20-litre vessel.
- The values for u'_0 and n in equation (8) may not be the same as those reported by Dahoe *et al.* (2001a) when the flow carries cornstarch particles. Although it was observed by Dahoe *et al.* (2001b) that the turbulent fluctuations of the gas phase appeared to behave independently from those of the particulate phase, and that this observation appears to be consistent with the implications of the Hinze–Tchen equation for the distribution of turbulent kinetic energy between the phases, further research is needed to shed light on this matter. Further research is also needed to find out whether the same value of n may be used to describe the behaviour of turbulence in the course of an explosion.
- Since the turbulent energy spectrum evolves in time as the turbulent energy decays, the turbulent length scale is not constant (Skrbek and Stalp, 2000). 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 equation (9), may have to be changed, going from gaseous to solid fuels. In addition, they may well differ for various types of dust, and for various particle size distributions for a given type of dust.
- 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 (Bardon and Fletcher, 1983). 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 (Mintz, 1993; Eckhoff, 2003), and no standardized test seems to be available.

Nevertheless, the described approach will be attempted used for various types of dust in the first version of DESC.

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, and isolation of explosions by fast acting valves, are already modelled, and the intension is to model suppression systems 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 (Cant *et al.*, 2004), since the overall system in which the flame propagates can be rather complicated to represent on the currently used Cartesian grid. Hence, the code could be a useful tool when designing process plants.

Simulations in this Work

The following sections explore some possible applications of a CFD-code for dust explosions. The model resulting from the experimental data for maize starch, shown in Figure 1, has been used in all simulations. 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.

VENTED SILO

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, and so on, on the maximum reduced explosion overpressure ($p_{red,max}$) generated by dust explosions inside enclosures. The dust dispersion and explosion experiments simulated in this section are described in detail by Hauert *et al.* (1994, 1996).

Experiments

Dust concentrations, velocities and rms turbulence velocities were measured at several positions in a 12 m^3 cylindrical silo, diameter 1.6 m and height 5 m. Various methods were used to generate dust clouds: pressurized dust reservoirs and ring nozzles, mechanical feeding, and pneumatic dust injection both tangentially and vertically

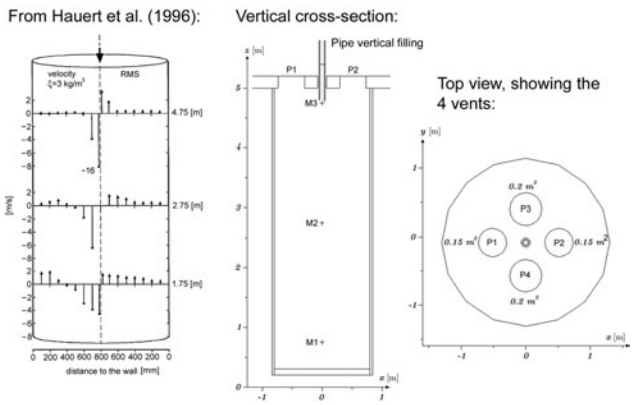

Figure 3. Measured vertical velocity and rms turbulence velocity for vertical filling of 12 m^3 silo, $\xi = 3$ kg m^{-3}, (left); vertical cross-section (centre) and top view (right) of simulated 9.4 m^3 silo.

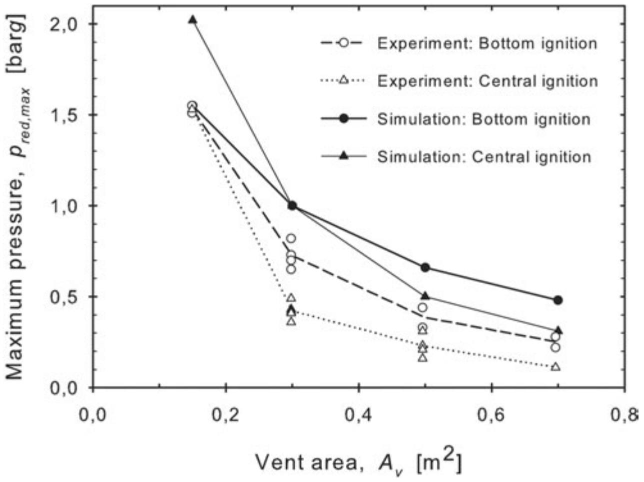

Figure 4. Simulated and experimental maximum reduced explosion pressures in a 9.4 m^{-3} silo as function of vent area for various ignition positions; experimental values from Hauert *et al.* (1996). Vertical filling: $\xi = 3$ or 5 kg m^{-3} in experiments, 5 kg m^{-3} simulated; $u_c = 22$–25 m s^{-1} in experiments, 23 m s^{-1} simulated.

downward. The pneumatic conveying velocity (u_c) was to set either 15 m s^{-1}, or to a maximum value of about 22–25 m s^{-1}. 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 3.

For explosion tests, the silo bottom was filled with sand; the silo volume was then reduced to 9.4 m^3. The silo was vented with polyethylene film, $p_{stat} = 0.1$ bar, and the following vent areas were used: 0.15, 0.3, 0.5 and 0.7 m^2. The ignition source was chemical igniters (10 kJ), located 0.75, 2.60 or 3.75 m above the silo bottom. For explosion tests with pneumatic injection, air was injected from a fan for 30 s, before a rotary air lock fed dust (maize starch: $K_{St} = 140$ bar m s^{-1}, $p_{max} = 9$ bar) into the line for another 30 s; ignition was triggered during dust injection. Exhaust air was let out through an outlet, diameter 75 mm, at the silo top. Some experimental results for explosions are plotted in Figure 4, for vertical dust injection rates $\xi = 3$ and 5 kg m^{-3}.

Simulations

A vertical cross-section of the simulated representation of the silo is shown in Figure 3, illustrating the coordinate system used, and three monitor points, M1–M3, located at $z = 0.75$, 1.75 and 4.75 m. Figure 3 also shows a top view of the modelled silo, illustrating the four vents, P1–P4. By setting the activation pressures for the four vent panels 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,

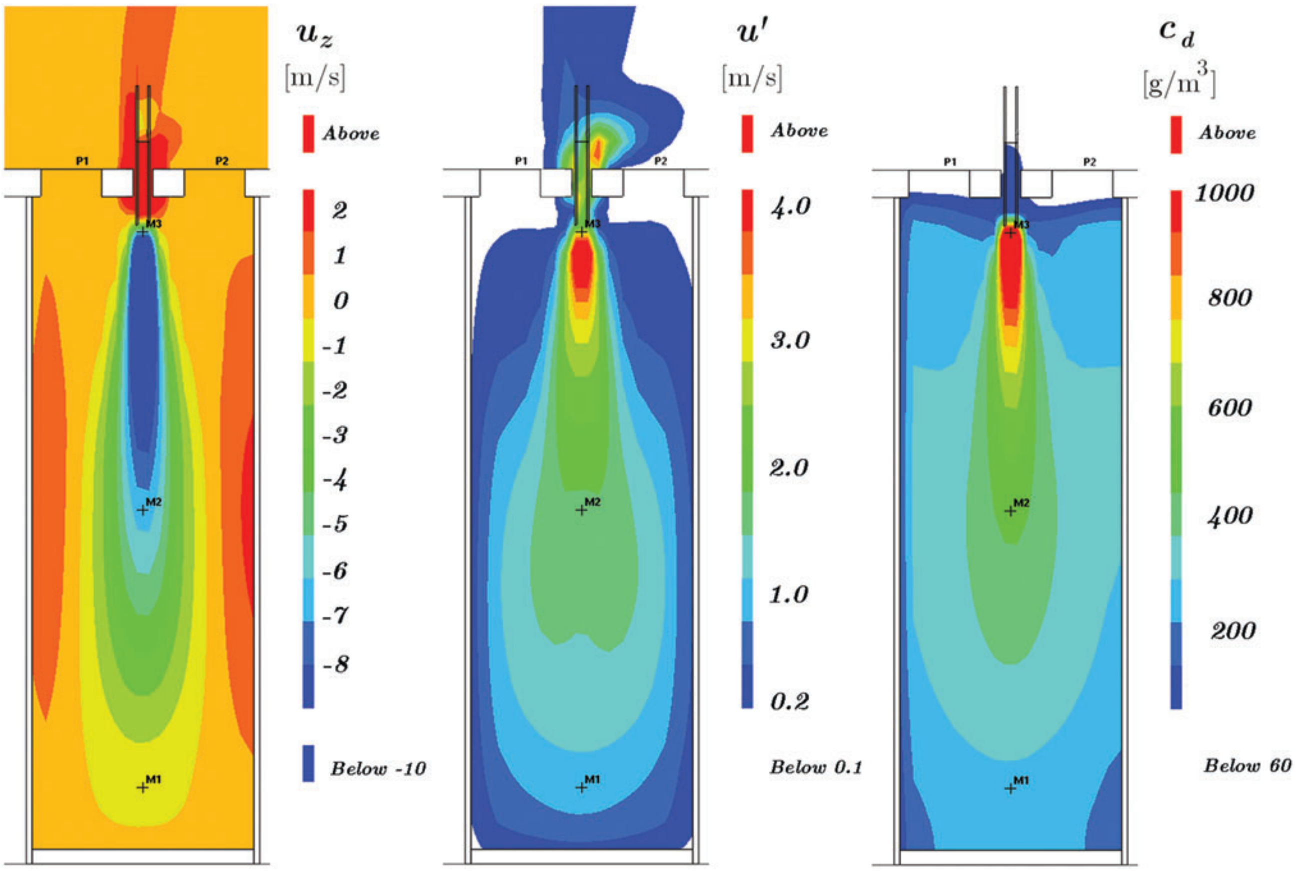

Figure 5. Simulated vertical velocity component (left), rms turbulence velocity (middle), and dust concentration (right) in 9.4 m^3 silo 9 s after onset of dispersion process. This figure is available online in colour via www.icheme.org/journals.

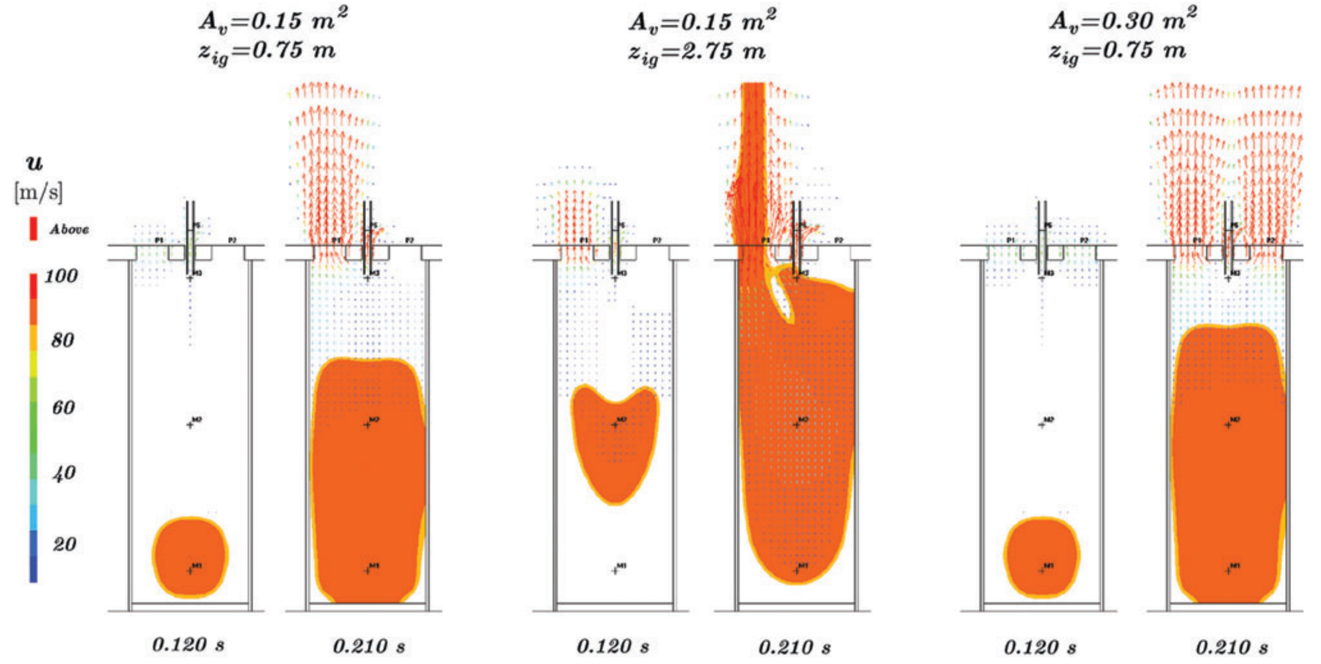

Figure 6. Simulated flame development (represented as combustion products) and velocity fields for various ignition positions (z_{ig}) and vent areas (A_v); two time steps are shown for each scenario, time relative to ignition after 9 s of dust dispersion. Simulated maximum reduced explosion pressures for the three scenarios are (from left to right): 1.6, 2.0 and 1.0 barg. This figure is available online in colour via www.icheme.org/journals.

0.3, 0.5 or 0.7 m^2. Cubical grid cells (0.1 m) were used in all simulations.

Only vertical pneumatic filling have been simulated ($\xi = 5\ \mathrm{kg\ m^{-3}}$, $u_c = 23\ \mathrm{m\ s^{-1}}$). 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 s of dust dispersion are illustrated in Figure 5; explosion simulations were started from these initial conditions for all vent 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 6, and simulated reduced explosion pressures are plotted in Figure 4 together with the experimental values.

Discussion

Simulated vertical velocities, and rms turbulent velocities, shown in Figure 5, are in relatively good agreement with experimental values, Figure 3. 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 experimental results to vent areas smaller than 0.15 m^2. Delayed outflow due to higher flow resistance for smaller vent areas, 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, may be one possible explanation for this phenomena; this scenario is illustrated in Figure 6.

INTERCONNECTED VESSEL SYSTEM

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, pressure rise due to an explosion in one part of the plant may compress an unburned explosible dust cloud in another interconnected part. If the precompressed cloud is ignited, very high pressures may occur if there is insufficient

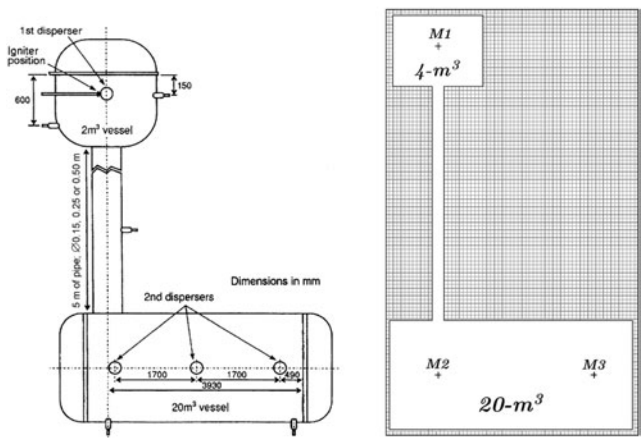

Figure 7. Interconnected vessel system: 2 m^3 vessel connected to a 20 m^3 vessel (left), from Lunn *et al.* (1996); cross-section of the system simulated in this work (right).

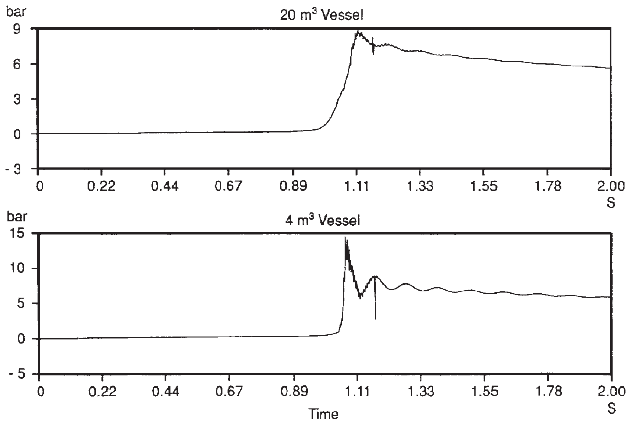

Figure 8. Pressure–time traces for coal dust explosion ignited in a 20 m^3 vessel connected to a 4 m^3 vessel by a 5 m long pipe, diameter 0.25 m, from Lunn *et al.* (1996).

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.* (1996).

Experiments

Lunn *et al.* (1996) investigated explosions of coal dust and toner for various configurations of linked vessels. Vessels with volumes 2, 4 and 20 m^3 were used; in each experiment, two vessels were connected by a 5 m pipe, diameter 0.15, 0.25 or 0.50 m. Dust was injected from pressurized reservoirs, and pressures were measured in both vessels, see Figure 7; an experimental pressure–time history illustrating pressure piling is shown in Figure 8.

Simulations

Only a configuration of two vessels, 4 and 20 m^3, connected by a 5 m long pipe with inner diameter 0.25 m, has been simulated, see Figure 7. 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, M1–M3, which also coincides with the three ignitions positions tested. Simulated pressure in the 4 m^3 vessel will be

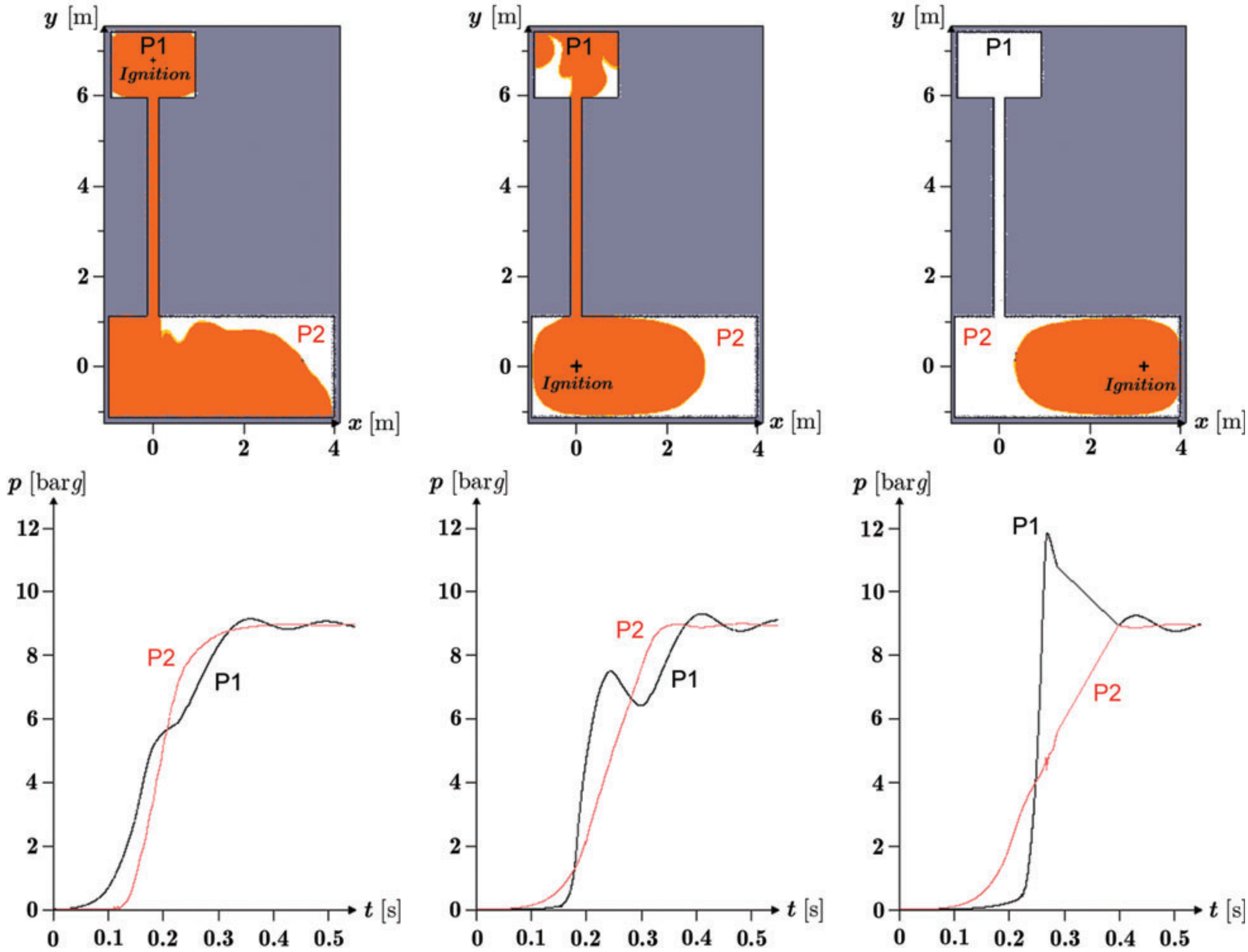

Figure 9. Simulated flame development, 0.18 s after ignition, in three different positions, for maize starch explosions (500 g m^{-3}) in a totally enclosed interconnected vessel system; the corresponding simulated pressure–time histories for the explosions are shown below each plots. This figure is available online in colour via www.icheme.org/journals.

referred to as P1, in the 20 m^3 as P2. 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 ($c_d = 500\ g\ m^{-3}$, $u' = 1.2\ m\ s^{-1}$, $LT = 0.05$ m). Pressure-time traces for the three ignition positions are shown in Figure 9, together with simulated flame development 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.

A major factor determining the success, or lack of success, of a CFD-code for dust explosions, will be the extent to which results from standardized tests in 20-litre explosion vessel can be correlated to fundamental combustion characteristics of dust clouds. Although the traditionally used K_{St} value seems to contain some information on the reactivity of combustible dusts, the transient nature of the tests makes it particularly challenging to extract quantitative information on the inherently complex phenomena involved in particle-laden flow and heterogeneous combustion. An alternative could be to determine fundamental combustion parameters, such as laminar burning velocity and flame thickness, in other types of laboratory tests, such as burners, pipe experiments, and even experiments in micro-gravity. Unfortunately, no such tests are standardized for the moment, and the possibility of introducing new tests that could complement or replace the currently used tests in 20-litre vessels is not a realistic alternative in the near future.

Since any CFD-code for dust explosions will have to be systematically validated against carefully planned experiments, increased understanding of the dust explosion phenomenon is likely to be gained through the development of new tools such as DESC.

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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This paper was presented at Hazards XVIII held in Manchester, UK, 23–25 November 2004. The manuscript was received 27 August 2004 and accepted for publication after revision 28 January.