

MODELLING OF VENTED DUST EXPLOSIONS – EMPIRICAL FOUNDATION AND PROSPECTS FOR FUTURE VALIDATION OF CFD CODES

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Explosion venting is the most frequently used method for mitigating the effects from accidental dust explosions in the process industry. Optimal design of vent systems and credible execution of risk assessments in powder handling plants require practical and reliable ways of predicting the course and consequences of vented dust explosions. The main parameters of interest include flame propagation and pressure build-up inside the vented enclosure, the volume engulfed by the flame, and the magnitude of blast waves outside the enclosure. Extensive experimental work forms the empirical foundation for current standards on vent sizing, such as EN 14491 and NFPA 68, and various types of software for vent area calculations simply apply correlations from these standards. Other models aim at a more realistic description of the geometrical boundary conditions, as well as phenomena such as turbulent compressible particle-laden flow and heterogeneous combustion. The latter group include phenomenological tools such as EFFEX, and the CFD code DESC (Dust Explosion Simulation Code). This paper briefly reviews the empirical foundation behind modern guidelines for dust explosion venting, and explores current capabilities and limitations of the CFD code DESC with respect to reproducing results from one experimental study on vented dust explosions. The analysis emphasizes the influence of geometrical features of the enclosures, discrepancies between laboratory test conditions and actual process conditions, and inherent limitations in current modelling capabilities.

KEYWORDS: Dust explosions, explosion venting, deflagration venting, DESC

INTRODUCTION

Dust explosions pose a hazard whenever a sufficient amount of combustible material is present as fine powder, there is a possibility of dispersing the material forming an explosive dust cloud within a relatively confined volume, and there is an ignition source present. The materials involved in dust explosion accidents have evolved with the development of industry. The dust explosion hazard was first recognized in the handling of grain, feed, and flour, as well as in coal mining operations, but accidents can occur with all types of finely divided combustible solids: agricultural products, foodstuffs, pharmaceuticals, chemicals, plastics, rubber, wood, metals, etc. Typical process units involved in industrial powder handling operations include mills, dryers, hoppers, cyclones, filters, chain conveyors, bucket elevators, systems for pneumatic conveying, and storage silos. For practical and occupational health reasons, combustible suspensions of particulate matter are usually contained within closed systems during normal operation, and explosion venting is the conventional method of mitigating the damaging overpressures that could otherwise result from dust explosions in such systems. Blast waves, secondary dust explosions, collapse of buildings, flame burns, projectiles, and subsequent fires are some of the major hazards to personnel and equipment outside a vented enclosure.

Venting guidelines specify the required vent area A_v for an enclosure, for a given set of parameters describing the enclosure, the venting device, possible vent ducts, and properties of the potentially explosive atmosphere inside the enclosure (Table 1). Current standards that contain venting guidelines include VDI 3673 (2002), EN14491 (2006), and

Table 1. Summary of some frequently used parameters for vent area calculations

Symbol	Description
A_f	Effective vent area
A_S	Internal surface area of vessel/enclosure
A_v	Geometric vent area
A_v/V_v	Classical vent ratio (units m^{-1})
$A_v/V_v^{2/3}$	Non-dimensional vent ratio (e.g. Tamanini, 1990)
D	Diameter or equivalent diameter of vessel/enclosure
$(dp/dt)_{ex}$	Maximum constant volume rate of pressure rise at given arbitrary concentration
$(dp/dt)_{max}$	Maximum constant volume rate of pressure rise at optimum concentration
$(dp/dt)_{red}$	Maximum reduced rate of pressure rise in vented enclosure
E_f	Venting efficiency: $E_f = A_f/A_v$
K_{St}	Size corrected maximum rate of pressure rise: $K_{St} = (dp/dt)_{max} V_v^{1/3}$
l_{vd}	Length of vent duct
L	Longest dimension of vessel/enclosure
L/D	Length to diameter ratio for vessel/enclosure
L_F	Flame length
P_{bw}	External overpressure outside enclosure (blast wave)
P_{ds}	Design overpressure, i.e. design strength of enclosure
P_{ex}	Maximum constant volume explosion overpressure at given arbitrary concentration
P_{max}	Maximum constant volume explosion overpressure at optimum concentration
P_{red}	Maximum reduced explosion overpressure in vented enclosure
P_{stat}	Static activation overpressure, i.e. the overpressure required to activate the venting device
t_v	Ignition delay time
V_v	Volume of vessel/enclosure

NFPA 68 (2007). Other standards specify experimental procedures for determining dust specific properties such as P_{max} and K_{St}: EN 14034 (2004; 2006) and ASTM E 1226 (2000). Together, these standards form the methodology for explosion protection by pressure relief venting adopted in Europe and North America. The correlations found in current venting guidelines originate from extensive experimental work, and design according to this methodology provides acceptable levels of safety in most situations. However, their empirical origin limits the extent to which vent area correlations apply to the great variety of process conditions encountered in industrial practice.

Recent developments of more advanced methods for predicting the consequences of industrial dust explosions include both phenomenological tools (Proust, 2005) and methods based on computational fluid dynamics (CFD). With proper modelling of the relevant physical and chemical phenomena involved in dust explosions, the predictive capabilities of such methodologies should extend significantly beyond the limited range of scenarios covered by past and possible future experimental work. However, it is nevertheless necessary to adopt some simplifying assumptions, since detailed modelling of all aspects of dust explosions is currently not within reach for industrial applications. Hence, extensive experimental verification is essential for building confidence in the new methodologies. With the currently limited prospects for funding of further large-scale experimental work on dust explosions, the available validation option is to utilize experimental results obtained in earlier campaigns. Unfortunately, however, it is usually not straightforward to simulate the original experimental conditions. Reliable data for the dusts used are often missing, including chemical composition, particle size distribution, specific heats, heat of combustion, and experimental pressure-time characteristics such as P_{ex} and $(dp/dt)_{ex}$ for the combustible concentration range. Furthermore, generation of explosive dust clouds often involve transient particle-laden flows that are inherently difficult both to measure and to model, and the initial dust distributions and levels of turbulence are therefore significant sources of uncertainty in most cases. Finally, many written sources only report a limited number of explosion characteristics, typically P_{red} and $(dp/dt)_{red}$, omitting important details of the actual pressure development and flame propagation.

The CFD code DESC (Dust Explosion Simulation Code) was developed to simulate industrial dust explosions in complex geometries, but there are still unresolved issues concerning the modelling approach (Skjold, 2007). Some of the main limitations in the current version (DESC 1.0) include inherent shortcomings in available turbulence models suitable for engineering applications, a simplified modelling approach to particle-laden flows (equilibrium mixture assumption), uncertainties concerning the validity of the correlations used to describe turbulent burning velocity, and lack of reliable models for flame quenching phenomena. The validation work has nevertheless produced promising results for certain vented dust explosion scenarios (e.g. Skjold *et al.*, 2005; 2006). The following sections review the empirical foundation behind currently used guidelines for dust explosion venting, and illustrate current capabilities and limitations of the CFD code DESC when it comes to reproducing experimental results obtained for vented dust explosions in a 64 m^3 vented enclosure at various levels of initial turbulence.

VENTING GUIDELINES – THE EMPIRICAL FOUNDATION

Pressure relief by release of combustion products and still unburned dust cloud through vent openings is presumably the oldest method of explosion protection for enclosures such as buildings and process units. Nevertheless, a majority of the early publications in this field focused primarily on preventive rather than mitigation measures, and most guidelines for vent sizing were primarily of qualitative nature. Following a series of disastrous explosions on the British Isles in 1911, one of the recommendations given by Her Majesties Inspector of Factories was simply: *"The roof should be such as to offer little resistance in the event of an explosion"* (Price & Brown, 1922). Since then, venting guidelines have become increasingly quantitative in nature. The following paragraphs review some highlights from the extensive experimental work that forms the empirical foundation for modern venting guidelines, with a view to the applicability of the results for future validation of CFD codes. Some brief comments on the evolution of standards on venting and experimental characterization of dusts are also included.

Some of the first systematic large-scale investigations on the effect of vent size and ignition position on vented dust explosions include the contributions by Greenwald & Wheeler (1925) and Brown & Hanson (1933). Both investigations demonstrated clearly that vent openings positioned close to the point of ignition provide the most effective pressure relief. Wheeler (1935) reported on dust explosion experiments with rice meal in a vertical 37.5 m^3 silo, $L/D = 4$, illustrating the pronounced influence of the vent area on P_{red}: fully open cylinder produced barely measurable overpressures, 2/3 open 0.03-0.04 bar, 1/3 open 0.3-0.4 bar, and 1/9 open in excess of 1 bar.

Hartmann (1954) presented results from a 1 ft^3 test gallery, demonstrating how the effect of vent ratio on P_{red} differ for various types of dust. Hartmann & Nagy (1957) emphasized that *"results from relatively small explosion chambers can be useful for protecting equipment and also for larger commercial structures"*; this statement was supported by experiments in cubical galleries having volumes 1, 64, and 216 ft^3, with and without vent ducts. The first standardized test vessels for measuring the explosion-pressure characteristics of dusts, i.e. P_{max} and $(dp/dt)_{max}$, were closed cylindrical vessels of relatively small volume: a 1.2 litre bomb introduced by Hartmann (Dorsett *et al.*, 1960), and a similar 1.0 litre bomb developed in England (Raftery, 1968). These tests have later been replaced with standardized tests in 20-litre explosion vessels.

Early quantitative guidelines for the calculation of vent areas relied on the classical vent ratio A_v/V_v. A typical example is the preliminary guidelines provided by NFPA (1946): *"For mild explosion hazards – 1 ft^2 for each 100 ft^3; for moderate explosion hazards – 1 ft^2 for each 50 ft^3; for severe explosion hazards – 1 ft^2 for each 15 ft^3; for extreme explosion hazards – maximum venting area obtainable"*. Palmer (1971) pointed out that the vent ratios method was limited to compact enclosures, i.e. enclosures having all three dimensions of the same order, and structures capable of withstanding pressures up to about 0.14 bar. Palmer mentioned the following guidelines for vent ratios, based on maximum rates of pressure rise determined in a 1.0 litre bomb: 1/6 m^{-1} (1/20 ft^{-1}) for $(dp/dt)_{max}$ less than 350 bar s^{-1}; 1/5 m^{-1} (1/15 ft^{-1}) for $(dp/dt)_{max}$ in the range 350 to 700 bar s^{-1}, and 1/3 m^{-1} (1/10 ft^{-1}) for $(dp/dt)_{max}$ exceeding 700 bar s^{-1}. Since A_v/V_v has dimensions $(\text{length})^{-1}$, estimates for very large enclosures yield unnecessarily large vent openings (Eckhoff, 2003). The American *'Standard on explosion protection by deflagration venting'* was first released as a temporary standard in 1945, and then replaced with a *'Guide for Explosion Venting'* in 1954, before major revisions followed in 1974, 1978, 1988, 1994, 1998, 2002, and 2007 (NFPA, 2007). The 1954 edition of NFPA 68 provided vent area recommendations based on the size and bursting strength of the enclosure.

The currently used venting guidelines in Europe originate from the extensive amount of experimental work reported by Donat (1971) and Bartknecht (1971; 1974ab), as well as the theoretical analysis by Heinrich & Kowall (1971). These contributions established the concepts of the K_{St} value and the cube-root-law: under given assumptions, the K_{St} value is a material specific constant for a given particle size distribution and a certain level of turbulence in the dust clouds at the time of ignition (Bartknecht, 1986). Unfortunately, it is practically impossible to achieve experimental conditions fulfilling the underlying assumptions behind the cube-root-law, but the overall concept is nevertheless valuable for practical applications. This work culminated in the first venting guidelines based on nomographs from Verein Deutscher Ingenieure (VDI) in 1979. Vent area correlations were introduced later (Siwek, 1994). The current European standard *Dust explosion venting protective systems* (EN 14491, 2006) is based on the VDI guidelines (Moore & Siwek, 2002).

The monumental experimental contribution from Bartknecht in the field of dust explosion safety comprises a vast number of experiments performed in vessels covering a wide range of scales and shapes (e.g. Bartknecht, 1971; 1986; 1993). In 1966 he introduced the standard 1-m^3 ISO vessel for determining reference values of P_{max} and $(dp/dt)_{max}$ (Bartknecht, 1971). A pneumatic dispersion system produced the dust cloud, and ignition after a specified time delay secured reproducible levels of turbulence. In the 1-m^3 vessel, dust is injected from a 5 litre container pressurized to 20 bar*g*, and the resulting dust cloud is ignited by two 5 kJ chemical igniters after 0.6 s. The larger enclosures were fitted with similar dispersion systems, but the number and volume of pressurized dust containers were chosen to achieve satisfactory distribution of the dust and sufficiently high levels of turbulent in the flow prior to ignition. Siwek (1977; 1988) demonstrated good agreement between results obtained in the 1-m^3 ISO vessel and a 20-litre spherical vessel. Several researchers have studied the dispersion induced flow and transient combustion phenomena in this 20-litre vessel, including Pu *et al.* (1990; 2007) and Dahoe *et al.* (1996; 2001abc), and the Siwek sphere is currently used for most of the experimental characterization of industrial dust samples. However, results presented by Proust *et al.* (2007) show that there can be significant differences between results obtained in the Siwek sphere and the standard ISO vessel. Regarding the validation of CFD codes, there are several challenges associated with the use of data from this type of experiments: the dust dispersion process involves transient turbulent particle-laden flow, and the turbulent combustion process takes place in a flow field characterized by rapidly decaying turbulence. The next section illustrates some of the challenges associated with such validation work.

Palmer (1975/76) summarised the status on dust explosion venting, emphasizing the need to strengthen the theoretical foundation. Other relevant contributions from this period include the ones by Rust (1979), Field (1984), Lunn (1989), and Siwek (1994). Several researchers presented experimental work where the dust was introduced into the enclosure by constant rate pneumatic conveying, e.g. Siwek (1989), Eckhoff *et al.* (1987), and Hauert *et al.* (1996). Such scenarios are more straightforward to model with modern CFD codes, compared to experiments with transient dust injection from a pressurized container (Skjold *et al.*, 2005; 2006). Eckhoff (1986, 1990) emphasized the need for a differentiated approach to vent sizing based on a risk assessments. Tamanini & Chaffee (1989) and Tamanini (1990) investigated the effect of turbulence on explosion severity in a vented 64-m^3 enclosure, and the next section illustrates the process of simulating these experiments with the CFD code DESC.

DECS SIMULATIONS – DUST EXPLOSIONS IN VENTED ENCLOSURE

Experiments reported by Tamanini (1990) and Tamanini & Chaffee (1989) demonstrate that the initial turbulent flow conditions influence the reduced overpressure from dust explosions in vented enclosures. The dusts used in the experiments were either maize starch or a blend of bituminous coal and carbon. Results from these tests inspired the vent design requirements for turbulent operating conditions included in the 2007 edition of the NFPA 68 guidelines (Zalosh, 2007). This section describes CFD modelling with DESC of the tests with maize starch, nominal dust concentration 250 g m^{-3}, vent ratio $A_v/V_v^{2/3} = 0.35$, ignition by a 5 kJ chemical igniter in the centre of the enclosure, and ignition delays in the range 0.5–1.1 s; these conditions cover seven of the totality of 21 original experimental tests. Results from experiments and simulations are compared, and the discussion focuses on the key assumptions, and hence the inevitable uncertainties, inherent in this type of validation work.

The experiments were conducted in a 64 m^3 vented enclosure with dimensions 4.6 × 4.4 × 3.0 m, design pressure 0.7 bar*g*, and an open 2.4 × 2.4 m vent door in one wall. Figure 1 illustrates the implemented geometry and computational grid used in the simulations. The grid inside the enclosure consisted of 0.1 m cubical grid cells for the dispersion simulation (cell size dictated by the maximum pseudo diameter of the transient release), and 0.1 or 0.2 m cubical grid cells for the explosion simulations (to illustrate the effect of grid resolution on the simulation results).

The explosion overpressures and K_{St} values for the maize starch used in the experiments were 6.1 bar and 144 bar m s^{-1} for a nominal dust concentration of 250 g m^{-3}, and 7.4 bar and 178 bar m s^{-1} for the optimum concentration of 800 g m^{-3}; the corresponding values for the sample used to generate the empirical combustion model for maize starch in DESC were 6.3 bar and 75 bar m s^{-1} at 250 g m^{-3}, and 8.6 bar and 150 bar m s^{-1} at 800 g m^{-3}. To compensate for the lower reactivity of the model sample, especially at 250 g m^{-3}, the estimated laminar burning velocity for the model dust was multiplied by a factor 1.75. As for most studies of this type, the reactivity of the model dust is a major source of uncertainty.

Tamanini and co-workers used a pneumatic injection system for dispersing the dust inside the enclosure: operation of fast acting valves discharged four 0.33 m^3 air tanks, initially charged to 8.3 bar overpressure, and the resulting airflow entrained and dispersed

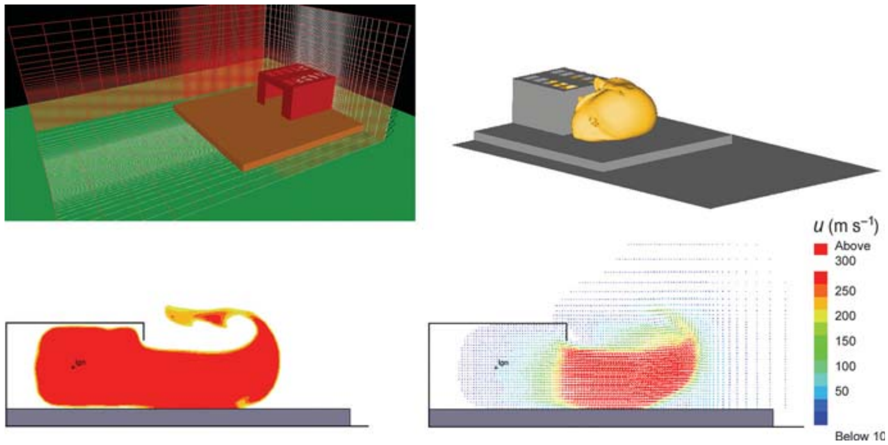

Figure 1. Geometry in DESC (above): grid (left) and flame ball exiting from the vent opening (right); the ten smaller vent openings on the top of the enclosure were blocked in both experiments and simulations. Cross sections of a part of the calculation domain (below), illustrating flame propagation visualised as mass fraction of combustion products (left) and velocity vectors (right)

dust from separate dust canisters through four perforated nozzles (i.e. 16 nozzles in total). The discharge stopped when the overpressure in the air tanks reached 1.4 bars. Several bi-directional velocity probes measured instantaneous velocities at various positions inside the enclosure during the injection process. Average and root-mean-square (RMS) turbulent velocities derived from these measurements indicated a high degree of non-uniformity of the flow field. In view of the importance of large-scale flow structures in the flow, *'the RMS of the instantaneous velocity was judged to be a more appropriate quantity to characterize the intensity of the turbulence inside the chamber'* (Tamanini, 1990). The RMS of the turbulent velocity fluctuations was roughly a constant fraction (60%) of the RMS of the instantaneous velocity fluctuations. The reported expected accuracy of the velocity measurements was 10-20% for velocity fluctuations with frequencies up to 400–500 Hz.

The DESC simulations imitate the actual dispersion process by introducing 16 transient leaks, releasing the same total amount of dust and air as in the experiments, from the same positions as the 16 original nozzles. It was not possible to resolve geometrical details of the perforated nozzles on the computational grid used here, but porous panels placed a few grid cells downstream of the leaks produced some spread in the flow from the nozzles. Figure 2 shows a comparison between experimental (with and without dust) and simulated turbulence intensities near the centre of the enclosure. A 0.1 s time shift in the simulated data accounts for the delay in opening the fast acting valves and charging the line between

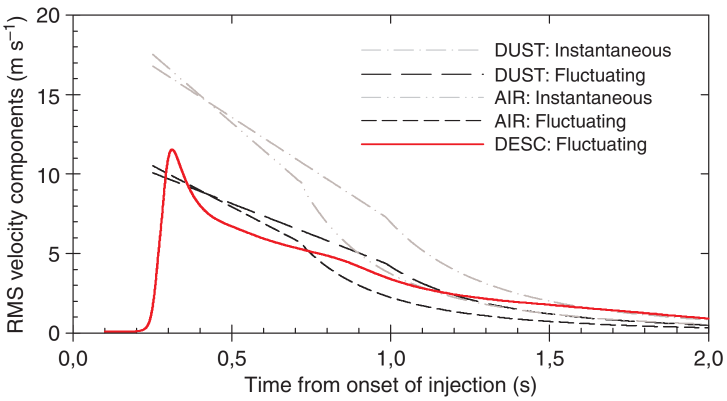

Figure 2. Measured instantaneous and estimated fluctuating velocity components, with and without dust, during the injection process in the $64\,m^3$ vented enclosure, and simulated fluctuating component (DESC)

the air tanks and the dispersion nozzles. Note that only the RMS of the fluctuating velocity components is relevant for comparison with the simulated values. Although the build-up time of the turbulent flow field is too long in the simulations, the simulated results are in reasonable agreement with measured values from about 0.3 s and onwards. The uncertainties in both measured and simulated values are nevertheless considerable. Turbulence measurements obtained with intrusive methods, such as bi-directional velocity probes, are not optimal, and it is generally very difficult to calculate the production of turbulence during the transient outflow of air through that takes place when a valve from a high-pressure tank opens quickly. Turbulence production during the initial phase of dispersion is probably largely due to the baroclinic term in the vorticity equation (Dahoe, 2001c), and current turbulence models for engineering applications, including the k-ε model used in DESC, are not able to accurately reproduce this phenomenon.

Figure 3 shows the measured increase in P_{red} for higher values of the average RMS of the instantaneous velocity. These results influenced resent modifications regarding turbulent flow conditions in the 2007 edition of NFPA 68 (Zalosh, 2007). The same Figure also shows results for two tests with other ignition sources (tests 21 and 22), one test with a smaller vent opening (test 10), and one test with a higher nominal dust concentration (test 6); stars indicate the experimental pressure traces that contained a distinct double peak (tests 3, 7 and 21).

Figure 4 illustrates the effect of ignition delay time and estimated RMS of the fluctuating velocity component (at the time pressures reach 0.8 P_{red}) on P_{red} and the average rate of pressure rise $(\Delta p/\Delta t)_{av}$ taken from 0.2 P_{red} to 0.8 P_{red}. Ongoing injection of dust at the

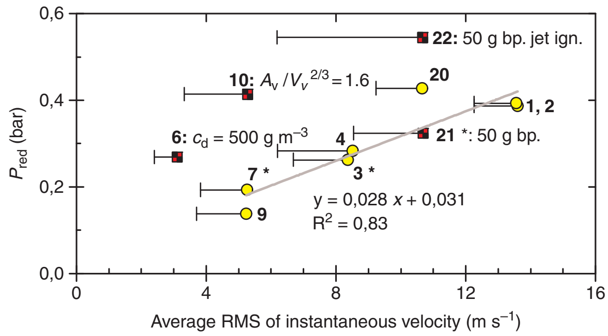

Figure 3. Effect of turbulence intensity at nominal time of ignition on P_{red} in 64 m^3 vented enclosure; original test numbers indicated for each data point, stars indicate double pressure peaks; error bars indicate RMS velocity at the time pressures reach 0.8 P_{red}; results from four tests with deviating experimental conditions included (bp. = black powder)

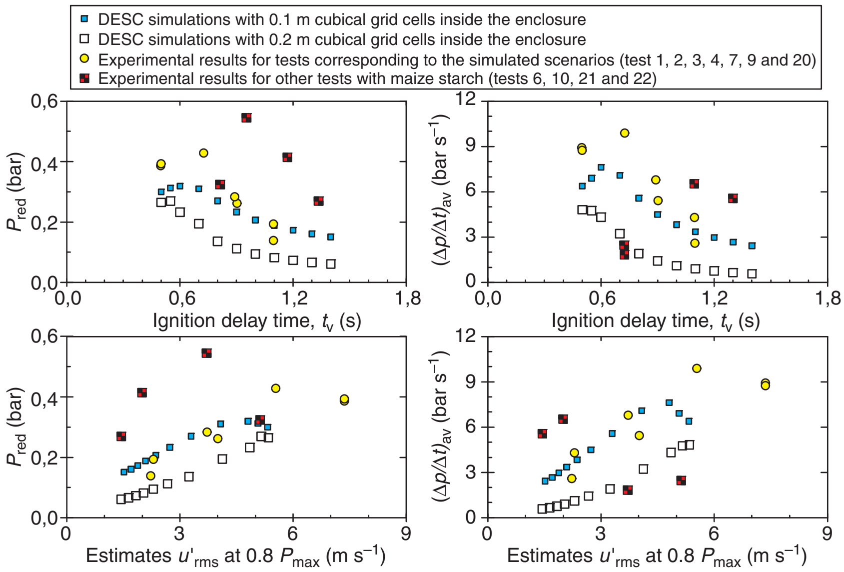

Figure 4. Experimental and simulated P_{red} and $(\Delta p/\Delta t)_{av}$ in the 64 m^3 vented enclosure for various ignition delay times and estimated RMS of the fluctuating velocity component at the time the pressure reaches 0.8 P_{red}

time of ignition results in the slight decrease in both P_{red} and $(\Delta p/\Delta t)_{av}$ for the shortest ignition delays and the highest turbulence intensities. The simulated values of both P_{red} and $(\Delta p/\Delta t)_{av}$ are too low at the shortest ignition delays, compared to experimental values, most likely due to the inability of the turbulence model in reproducing the high initial rates of turbulence production. For longer ignition delays, the experimental and simulated results are in better agreement. However, Figure 4 also reveals a significant effect of the computational grid on the simulation results. The flame model in the current version of DESC yields a flame that is three grid cells thick, and one reason for the higher rates of energy release inside the enclosure for the smallest grid cells is the fact that a finer grid resolution results in a thinner flame and a larger flame area. In future versions of DESC, local properties of the flow field, such as the RMS of the turbulent velocity fluctuations and the turbulent integral length scale, as well as dust specific parameters such as laminar burning velocity and laminar flame thickness, should determine both the turbulent burning velocity and the turbulent flame thickness. Turbulent combustion in dust clouds exhibits a high degree of volumetric combustion, and a fuel and flow dependent flame thickness that accounts for this phenomenon should produce less grid dependent results. The difference in rates of combustion between a coarse and a fine grid is enhanced for scenarios where ignition takes place in a flow field characterized by rapidly decaying turbulence. This effect is due to a too low rate of combustion during the initial phase of combustion, where a subgrid model governs the rate of growth of the flame ball up to a flame radius of about three grid cells. On a finer grid, it takes shorter time for the initial flame ball to reach a size where the subgrid model no longer governs the further rate of flame growth. Hence, due to the rapid decay of turbulence, the flame on the finer grid propagates through a flow field characterized by somewhat higher turbulence intensity, as compared to the flame on the coarser grid.

Enclosures with moderate L/D ratios yield the most pronounced effect of dispersion-generated turbulence on P_{red}. For enclosures with larger L/D, the influence of ignition position and explosion-generated turbulence dominates (e.g. Eckhoff, 1992).

CONCLUSIONS

The experimental work invested in developing, validating, and improving guidelines for explosion protection by venting represents a vast amount of information on flame propagation in dust clouds. Hence, in principle there is no doubt that such data represents a unique possibility for validating modern CFD codes. However, modelling of typical large-scale dust explosion experiments is a challenging task, not only because of the inherent complexity of particle-laden flows and turbulent combustion, but also due to the transient nature of the experimental procedures often adopted in this type of dust explosion research. Furthermore, the level of details included in descriptions of original experimental equipment, procedures, and results varies significantly, and some sources report only selected variables such as the maximum reduced explosion pressure and the maximum reduced rate of pressure rise. Future validation work for CFD codes is nevertheless likely to benefit significantly from previous experimental work, and it seems inevitable that our understanding of dust explosions will increase with improved modelling capabilities in the future.

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