Simulation of dust explosions using a CFD-code

by

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1 INTRODUCTION

Guidelines and methods that are used today to protect people and installations against the consequences of dust explosions are all based on pure experimental research. Important examples are the work performed to arrive at venting guidelines including the effect of vent ducts and the work to develop guidance for installation of active isolation techniques such as fast-acting sliding valves and barriers using extinguishing agents which involves knowledge on the propagation of dust explosions through pipelines.

The experimental work has beyond any doubt led to a great improvement of the understanding of dust explosion propagation mechanisms and as a result the level of safety in industry.

There are several questions which remain, however, and they are all related to the extrapolation of the results beyond the conditions prevailing during the experiments.

In this paper it is argued that there is a need for a capability to simulate dust explosion propagation in geometries deviating from those used in experiments and for initial process conditions deviating from experimental conditions using a CFD-code.

The results of a first attempt using the CFD-code FLACS (=Flame ACceleration Simulator) carried out as part of the CEC-sponsored project CREDIT are presented. FLACS has originally been developed for simulation of gas explosions in congested environments such as offshore modules.

2 THE NEED FOR SIMULATING DUST EXPLOSIONS

The need for simulating dust explosions using a CFD-tool is argued by presenting several examples. These examples, taken from literature, show that guidelines based on experiments sometimes may result in a considerable overestimation of the effects but there may also be situations where an underestimation is possible or where a prediction cannot be given.

2.1 Pre-ignition process conditions

In order to determine the relative reactivity of dust-air mixtures tests are performed in a vessel of 1 m^3 or 20 l capacity. To mix the dust with air the dust is blown into the vessel through a nozzle from a pressurised vessel. After a fixed delay time ignition is effected and the evolving pressure-time history is measured [1]. From this pressure-time history parameters such as the K_{St}-value and maximum explosion overpressure are obtained which are used as input parameters for determining vent openings according to internationally accepted guidelines. This technique for generating dust clouds is standardised and gives a standard initial degree of turbulence. The same technique of generating turbulence has been used to arrive at venting guidelines such as the German VDI 3673 [2] and the UK IChemE guidelines [3]. In general explosion effects increase with increasing degree of pre-ignition turbulence: the stronger the turbulence the higher the combustion rates will be and the larger the vent openings should be to protect structures from being damaged by dust explosions. The degree of pre-ignition turbulence, however, may be considerably lower than established by standardised experimental conditions. Examples of experiments illustrating this are experiments performed under normal operating conditions performed in bag filters [4, 5], in silos using pneumatic injection [6, 7], vessels using pneumatic injection [8] and cyclones [9].

Figure 1 shows overpressure generated in a 20 m^3 slender silo as a function of vent area on top of the silo for maize starch dust explosions. Three different dust injection were used: the standardised technique, pneumatic feeding (axial) and dust feeding via a cyclone and rotary lock. These techniques lead to three different levels of pre-ignition turbulence and in addition to that relative differences in the homogeneity of the clouds. The Figure shows the importance of the initial conditions on the overpressure generation.

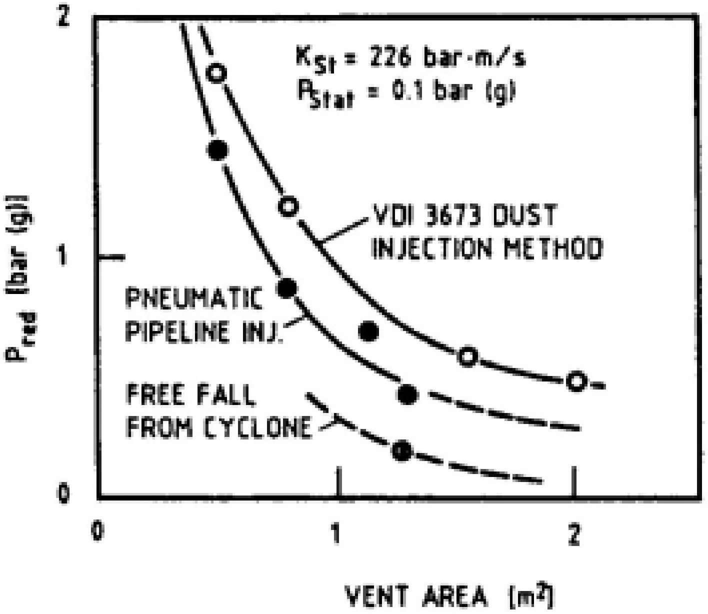

Figure 1 Results from vented maize starch explosions in a 20 m3 silo for three different modes of dust cloud generation [7].

It would be very expensive to perform explosion experiments for any degree of pre-ignition turbulence in the various industrial installations that exist (scale and turbulence intensity) such as filters, dryers and silos. With the help of a computational fluid dynamic tool provided with good physical sub-models such as models for turbulence generation and dissipation, behaviour of dust particles in flowing media and combustion it would be possible to predict the structure of the flow field and dust cloud characteristics before ignition and the propagation of the flame and associated pressure development in all these types of equipment without having to perform many experiments.

2.2 Geometrical aspects

A second important factor which may influence the consequences of a dust explosion considerably is the generation of turbulence by the expansion flow due to the combustion. Such flame generated turbulence may arise in slender silos, long pipes, integrated systems consisting of several vessels and interconnecting pipelines and conveyors (such as elevators). The expanding combustion products will onset a flow field ahead of the flame resulting in turbulence on walls and obstructing elements such as the buckets in an elevator. The turbulence will affect the combustion rate increasing the rate of combustion products generating and hence expansion flow. The increased flow rate ahead of the flame will cause more intense turbulence increasing the combustion rate etc.. This positive feedback mechanism may result in overpressures exceeding those when one would apply simple venting guidelines. The guidelines will however not be applicable for these types of equipment or will have general conservative rules. Examples of flame accelerations in equipment are the silo experiments described in [6], the interconnected vessel experiments described in [10], pneumatic conveying systems [11] and pipelines [7, 12].

The recent experiments in interconnected vented vessels performed in the UK [13] resulted in guidelines for venting of two interconnected vessels but the possibilities for extrapolation are limited.

A CFD-tool describing turbulence generation on walls and obstructions during combustion will allow for such extrapolations, including the effects of bends in pipelines, the shape of obstructions, dimensions, position of vents, etc.

2.3 Secondary effects

Venting of dust explosions will lead to flame and pressure effects around the vented structure. Depending on where ignition is effected in the structure a large cloud of unburned dust will be pushed out of the vent opening. Due to the outflow through the vent this dust-air mixture will be turbulent. Upon the flame emerging from the vent the external cloud will be ignited causing a strong explosion outside the protected structure causing a flame ball and pressure effects in the surroundings. This may cause damage outside the protected structure. Nearby windows may break and/or people may be endangered.

Experiments have been performed to study these effects and to provide guidance with respect to the prediction of external effects [14, 15]. The experiments and therefore guidelines cover simple situations only (a single vent, one direction). The use of a CFD-tool would allow for studying the effects outside vented structures for any situation, multiple vent openings, various directions, effects of structures outside the vent, etc.

3 INTEGRATION OF DUST COMBUSTION MODEL IN CFD-TOOL

In this chapter the integration of a dust combustion model in the FLACS explosion tool is described. The integrated model has been validated against experiments performed in a 20 m^3 room.

3.1 Short description of the FLACS code

FLACS is a fluid dynamic code developed for description of gas dispersion and explosion processes in complex geometries such as offshore modules [16]. FLACS calculates explosion pressure and other flow parameters as a function of time and space for different geometries and explosion scenarios. It takes account of the interaction between flame, vent areas and obstacles such as equipment and pipe work. The FLACS code solves the full gas dynamic partial differential equations for a set of control volumes. The effects of turbulence and chemical reactions are included in the differential equations. The equations are discretised using a finite-volume technique and a weighted upwind/central differencing scheme for the convection terms. Velocities are calculated on staggered grids. The effect of turbulence is included through the eddy viscosity concept by solving equations for turbulent kinetic energy (k) and its rate of decay (ε).

3.2 Implementation of a dust combustion model

To be able to simulate dust explosions using the FLACS code a dust combustion model has to be implemented. For gas explosions a model is used based on the flame library developed at Leeds University [17]. The same workers showed that a similar approach as accepted for gas explosions can be used for dust explosions [19]. Several institutions have been working on such a model describing the basic combustion properties as a function of turbulence parameters. Figure 2 shows an example of such research. The Figure shows the variation of the turbulent burning velocity S_T as a function of the turbulence intensity u’ for maize starch-air mixtures (from [18]). Both turbulent burning velocity and the turbulent intensity have been normalised by the laminar burning velocity S_L. The data evolve form experiments performed in a 0.95 m^3 spherical bomb. Turbulence was generated by a recirculation system. As the Figure shows a single relationship was found for two maize starch-air mixtures. The normalised turbulent burning velocity increases linearly with the normalised turbulence intensity.

For gaseous fuels the linearity of the relationship breaks down at high turbulence intensities and may even lead to flame quenching. For dust-air mixtures one would expect a similar development. Experiments reported in [20] considered a channel where four fans generated a turbulent flow field. A cloud of dried wheat was produced and ignited. The flame speed was measured as a function of the fan speed, i.e. turbulence intensity. Initially the flame speed increased with fan speed as one expect according to the relationships presented in Figure 2 but with further increase of the fan speed the flame speed decreased. This flame speed decrease is attributed to quenching by very intense turbulence. Regarding optimal dust-air mixtures such high

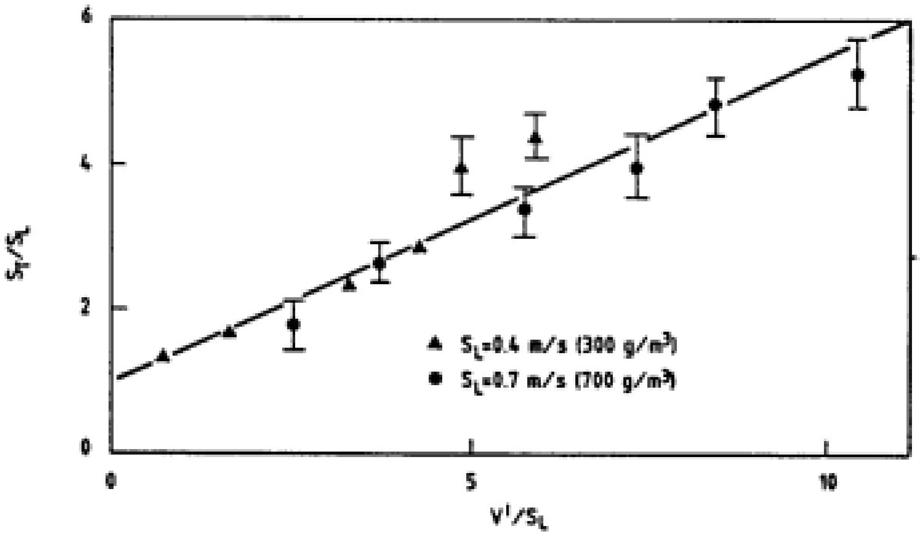

Figure 2 Variation of turbulent velocity S_T with turbulence instensity u’ for maize starch-air mixtures. Both the turbulent intensity and turbulent burning velocity have been normalised by the laminar burning velocity S_L.

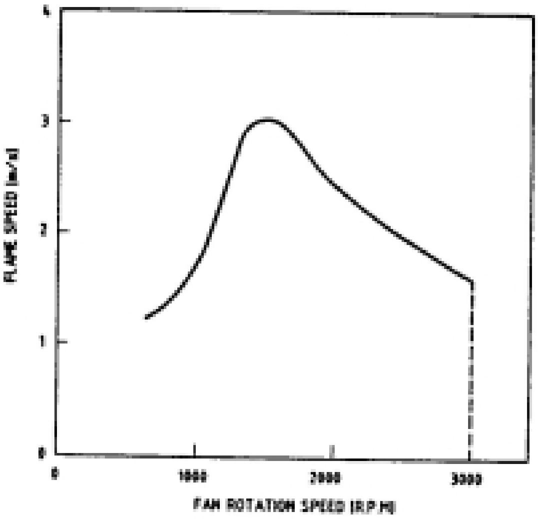

Figure 3 Flame speed as a function of rotational fan speed for wheat dust in a channel.

degrees of initial turbulence which are capable of quenching dust flames will only exist in very fast rotating equipment such as mills or jet mills.

Quenching of dust flames has also been noted in explosions involving combustion generated turbulence in integrated systems [10, 13]. The results reported in [10] show that the quenching occurs easier for low reactive mixtures.

The gas and vapour combustion model described in [17] also takes the turbulence integral length scale into account.

A dust combustion model should take all these elements into account as well, i.e. effect of turbulence intensity, turbulence integral length scale on combustion rate and possibly quenching when the turbulence intensity is too high (for a given length scale).

At the Warsaw University of Technology a combustion model was being developed on the basis of experiments in a 1.25 m^3 spherical explosion bomb [21]. The experiments involved variation of the turbulence intensity. Rates of pressure rise and flame velocities were measured directly. The experiments were performed for lycopodium, wheat and maize starch. The experiments allowed for estimating turbulent burning velocities as a function of the turbulence intensity but in addition to that the experiments allowed for estimating the effect of pressure and temperature due to adiabatic compression of the unburned mixture on flame propagation. The experiments do not allow for investigating the effect of turbulence length scale on flame propagation.

The model reflects the results shown in Figure 2: a linear increase of the turbulent burning velocity with turbulence intensity:

$$S_T = S_L + Ku'$$

The coefficient K is a dust dependent coefficient: K=0.37 for lycopodium, K=0.16 for wheat and K=0.46 for maize starch.

The other input parameter the laminar burning velocity can be measured in ducts or tubes closed at the top and opened at the bottom. Dust is fed at the top, ignition is effected at the bottom. Table 1 shows examples of measured laminar burning velocities (results from [21, 22]).

Table 1 Examples of laminar burning velocities

Dust type	Dust-air concentration (g/m^3)	Laminar burning velocity (m/s)
Lycopodium [21]	230	0.7
Lycopodium [22]	175	0.41
Wheat dust [21]	390	0.95
Maize starch [21]	700	0.59
Maize starch [22]	300	0.55

In addition to the combustion model a model describing the effect of temperature and pressure on the turbulent burning velocity was developed and implemented in the CFD-tool. For all dusts a single relationship was found, viz.:

$$S_{T,T} = S_{T,0}(T/T_0)^{1.7}$$

where $S_{T,T}$ = turbulent burning velocity at temperature T
$S_{T,0}$ = turbulent burning velocity at temperature T_0
The relationship does not include any pressure dependency since the experiments revealed a very minor pressure dependency only.

3.3 Validation of code

The FLACS-code provided with the dust combustion model described above has been validated against experiments performed in a 20 m^3 room (dimensions 2.4 m x 2.4 m x 3.6 m). The room was provided with vent areas of 1 and 1.44 m^3 respectively. The very experiments were carried out with maize starch (concentration 750 g/m^3). The dust-air mixture was generated using the standardised way of generating dust-air mixtures. Instead of ring-shaped nozzles, however, pepper boxes were used to disperse the dust and instead of a delay time of 600 ms a delay time of 900 ms was used. The vent opening was covered with a vent cover opening at a static opening pressure of 0.08 bar. Ignition was effected either in the centre of the room or at the rear wall.

The pressures were measured inside the enclosure and outside the enclosure at several distances from the vent opening. The experimental results are presented in the Table below.

Table 2 Results of vented explosion experiments carried out in a 20 m^3 room using maize starch as a flammable dust [15].

Scenario no.	Vent opening size (m2)	Ignition location	Overpressure (bar)
1	1.44	rear wall	0.33-0.35
2	1.44	centre	0.20-0.25
3	1.0	centre	0.66

To be able to simulate these experiments several input parameters must be chosen such as:

- the degree of initial turbulence
- the laminar burning velocity of the fuel

To generate the dust cloud the dust was injected from pressurised hoppers in the roof of the test chamber. After a delay time of 900 ms ignition was effected. The degree of pre-ignition turbulence was not measured and therefore had to be estimated.

In [23] experiments are described where the turbulence intensity was measured in a 1 m^3 vessel while using the standard way of generating dust clouds [1]. The results show first of all that the turbulence is not isotropic as assumed when using a k-ε model in a numerical model to describe turbulence. The non-isotropic turbulence field is caused by the arrangement of the ring-shaped nozzle. The measurements revealed turbulence velocities of 1.2 m/s and 5.36 m/s for the two components that were measured (horizontal and vertical components respectively) at a delay time of 600 ms. For a delay time of 900 ms (as used in [15]) turbulence velocities of 0.7 m/s and 2.72 m/s were measured.

The experiments described in [15] were performed with an initial turbulence level controlled by adjusting the dust dispersion pressure and ignition delay. The adjustment was such that the internal overpressure obtained under the experimental conditions with central ignition was in accordance with the VDI 3673, nomograph approach [24]. This implied a delay time of 900 ms as mentioned above.

This would imply a turbulence intensity of 1.2 to 5.36 m/s assuming a similar turbulence length scale as in the 1 m^3 vessel. Regarding the use of isotropic turbulence in the k-ε model one can assume a turbulence intensity of 3.28 m/s.

The turbulence length scale will affect both the burning rate and the rate of turbulence dissipation. The combustion model that has been developed by the Warsaw University of Technology does not describe the effect of turbulence length scale on the combustion rate and could therefore not be taken into account in the present study. The rate of turbulence dissipation is of paramount importance for the course of the dust explosion since turbulence dominates the rate of combustion. The faster the rate of dissipation, i.e. the smaller the turbulence length scale, the lower the overpressure generated in the 20 m^3 chamber will be.

The second parameter that has to be known to be able to use the model is the laminar burning velocity S_L. Measurements were performed by both Christian Michelsen Research and the Warsaw University of Technology. The results have been presented in Table 1. The 20 m^3 chamber explosion experiments were carried out for a concentration of 750 g/m^3. The laminar burning velocities were not measured for such a high concentration. On the basis of relationship between K_{St}-value and dust concentration, however, a laminar burning velocity of S_L=0.7 m/s was chosen.

The correction for pressure and temperature increase during the course of the explosion was performed using the relationship developed by [21] and presented before.

Some simulation results are presented in Table 3. The input parameters were as mentioned above. The main unknown factor is the turbulence at the moment of ignition. For the turbulence intensity a reasonable estimate could be made on the basis of 1 m^3 vessel turbulence measurements. For the turbulence integral length scale, however, only a rough estimate can be made. The results in Table 3 show explosion overpressures for the three scenarios using turbulence length scale of 1 cm and 24 cm.

As such the turbulence length scale can be chosen such that the simulation results would agree with the experimental results reducing the value of this validation exercise.

Table 3 Results of simulations of dust explosions in a vented 20 m^3 chamber using maize starch using turbulence integral length scales l_t of 1 cm and 24 cm.

Scenario no.	Vent opening size (m2)	Ignition location	Press. Exp. (bar)	Press. Sim. (bar) l_t = 1 cm	Press. Exp. (bar) l_t = 10 cm
1	1.44	rear wall	0.33-0.35	0.12	0.5
2	1.44	centre	0.20-0.25	0.1	0.38
3	1.0	centre	0.66	0.15	0.85

4 CONCLUSIONS

It has been argued that there is a need for developing a numerical code capable of describing the course of dust explosions dependent on process conditions and geometrical aspects.

The results of a first attempt on the basis of a code developed for simulating gas explosions in complex geometries has been undertaken. A combustion model developed at the Warsaw University of Technology was implemented.

A validation against dust explosion experiments carried out in a 20 m^3 vented chamber highlighted the need for measurements of the turbulence prevailing in the room at the moment of ignition. This would apply to any experiment that is used for validation of a numerical tool since the generation of a dust cloud without causing turbulence is hardly possible.

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