Flame Propagation in Dust Clouds: Challenges for Model Validation

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Modelling of industrial dust explosions poses a formidable challenge to researchers and safety engineers. Whereas current best practice with respect to modelling the consequences of vapour cloud explosions in the petroleum industry involves the use of computational fluid dynamics and a probabilistic approach to risk assessment, current safety practice for powder handling plants still rely on empirical guidelines. Although there has been significant progress in the predictive capabilities of phenomenological tools and CFD codes in recent years, such methods still require further development and verification. The first part of the paper contains a brief review of medium to large-scale dust explosion experiments suitable for validating consequence models for dust explosions. The second part demonstrates typical modelling challenges by simulating selected experiments from a study of vented explosions in a connected vessel system with the CFD code DESC. The simulation results are evaluated based on comparison with experimental results, and with respect to the observed response to moderate variations in the input parameters. Finally, the discussion highlights main knowledge gaps with respect to available experimental data and current modelling capabilities.

Keywords: dust explosions, computational fluid dynamics, validation, process safety

1. Introduction

Dust explosions continue to pose a hazard in the process industries, in spite of numerous efforts to improve legislation, standards, and best practice guidelines over the past century (Price & Brown, 1922; Bartknecht, 1993; Eckhoff, 2003). One reason for this is the fact that dust explosions are inherently complex phenomena, involving transient turbulent reacting particle-laden flows, often in relatively complex geometries. In addition, several mechanisms may contribute to escalating accident scenarios, including the positive feedback between explosion-induced flow and turbulent flame propagation, lifting and dispersion of settled dust layers, pressure piling, and secondary explosions both inside and outside process equipment and buildings.

Dust Explosion Simulation Code (DESC) was a project supported by the European Commission. The main purpose of the project was to develop a simulation tool based on computational fluid dynamics (CFD) that could predict the potential consequences of industrial dust explosions in complex geometries. Partners in the DESC consortium performed experimental work on a wide range of topics, including dust lifting by flow or shock waves, flame propagation in vertical pipes, dispersion induced turbulence and flame propagation in closed vessels, dust explosions in closed and vented interconnected vessel systems, and measurements in real process plants. The CFD code DESC is based on the existing CFD code FLACS (FLame ACceleration Simulator) for gas explosions, but the modelling approach entails the extraction of combustion parameters from pressure-time histories measured in standardised 20-litre explosion vessels (Skjold, 2007a).

It may not be necessary to adopt advanced modelling tools for estimating the consequences of a dust explosion. Current standards and guidelines work reasonably well for design of explosion protection systems in simple geometries, such as silos and isolated process vessels. Numerous experimental studies describe such systems, including Brown & Hanson (1933), Wheeler (1935), Bartknecht (1971), Bartknecht (1974ab), Bartknecht (1986), Eckhoff *et al.* (1987), Tamanini (1990), Bartknecht (1993), Hauert *et al.* (1996) and Siwek *et al.* (2004), and the results have been used for validating DESC and other CFD codes in the past: Skjold *et al.* (2005, 2006, 2008), van Wingerden & Skjold (2008) and van Wingerden *et al.* (2009).

However, advanced modelling capabilities are desired for the design of explosion protection systems in industrial-scale powder handling plants with relatively complex geometries. The number of experimental investigations described in the open literature is significantly lower for such systems, compared to isolated vessels and silos. Many experimental investigations have focused on explosions in mine galleries, including Greenwald & Wheeler (1925) and Lebecki *et al.* (1993, 1995). These studies were used for validating the dust lifting model in DESC (Skjold, 2007b; Skjold *et al.*, 2007). Lunn *et al.* (1996) described experiments performed by Health and Safety Laboratory (HSL) in a totally enclosed interconnected vessel system, and some of the tests were simulated with the first version of DESC (Skjold *et al.*, 2005). Other experiments in relatively complex geometries may prove useful for future model evaluation: bucket elevators (Holbrow *et al.*, 2002), filter systems, pneumatic conveying systems (Vogl & Radant, 2005), etc.

The remaining parts of this paper will focus on a series on large-scale explosion experiments in an interconnected vented vessel system performed by HSL during the DESC project. Skjold (2007a) presented simulation results obtained with DESC for one of the tests, but the current study entails a more thorough study of several tests with coal dust.

2. Dust explosion experiments in an interconnected vented vessel system

As part of the DESC project, HSL performed a series on large-scale explosion experiments in interconnected vented vessels (Holbrow; 2004, 2005). Figure 1 shows a schematic representation of the experimental setup. Two cylindrical vessels, volumes 20 m^3 and 2 m^3, were connected by two 5 m pipes with a sharp 90^o bend. The pipe diameter was either 0.50 or 0.25 m, and the vent openings on the 20 m^3 and 2 m^3 vessels were 0.9 m^2 and 0.19 m^2, or 1.5 m^2 and 0.33 m^2, respectively. The dust-air suspensions were ignited in the largest vessel after a preset ignition delay time of 0.5 s, measured from the activation of the valves controlling the dispersion system. The ignition source was an electrical fuse head, placed inside a polyethylene bag containing 25 grams of black powder, release about 50 kJ of energy. The position of the ignition source was in the centre (1), at the rear wall (2), or at the side wall (3) of the 20 m^3 vessel.

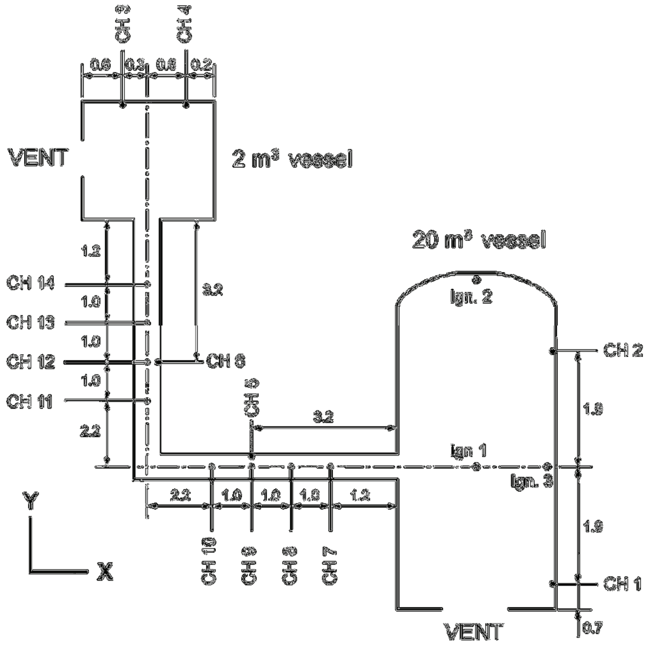


Figure 1: Schematic of interconnected vessel system, showing instrument location.

Six pressure transducers, CH1-CH6, were located in the vessels and in the pipe, and eight 1.5 mm exposed junction thermocouples (type K), CH7-CH14, measured flame arrival along the centre-line of the pipe. Only measured voltages from the thermocouples were reported, not temperatures.

The experimental program included 34 tests, including eight commissioning tests with isolated vessels (four tests in each vessel), with four types of dust: coal, silicon, and two types of potato starch. Explosions transmitted more readily through the 0.50 m diameter pipe than through the 0.25 m diameter pipe, and explosions involving potato starch were more likely to transmit to the secondary vessel than the more reactive coal dust. Where no transmission occurred, the flame extinguished close to the 90^o bend.

Only test 13 produced significant pressure enhancement in the secondary vessel. This test involved coal dust, the smallest vent openings on both vessels, and the 0.5 m diameter pipe. Table 1 summarises the results for all the tests with coal dust. The nominal dust concentration was 500 g m^{-3} in all tests. Unfortunately, only tests 18 and 19 are repeats for the same experimental conditions, and although the measured pressures are very similar for these tests, the explosion propagated to the secondary vessel in test 18, but not in test 19.

With respect to model validation, and in particular for CFD models where the aim is to describe flame propagation in complex geometries, it is expedient to focus on the experimental conditions that resulted in significant pressure piling in the secondary vessel. Hence, the remaining parts of this paper will focus on tests 13, 34 and 33, where the only controlled variation in experimental conditions is the position of the ignition source in the primary vessel.

Table 1: Summary of the experiments with coal dust (Holbrow; 2004, 2005).

Test No.	20 m³ Vessel					Connecting pipe			2 m³ Vessel			
	A_v [m²]	Ign. pos.	P_{stat} [bar]	P_{CH-1} [bar]	P_{CH-2} [bar]	D_{pipe} [m]	P_{CH-5} [bar]	P_{CH-6} [bar]	A_v [m²]	P_{CH-3} [bar]	P_{CH-4} [bar]	Explo. trans.
13	0.9	1	0.11	**0.52**	**0.56**	0.50	**1.85**	**2.10**	0.19	**2.84**	**2.86**	1
34	0.9	2	0.10	0.38	0.41	0.50	0.39	0.30	0.19	0.34	0.25	0
33	0.9	3	0.11	0.11	0.13	0.50	0.09	0.10	0.19	0.10	0.10	1
22	0.9	1	0.09	0.35	0.38	0.25	0.28	0.16	0.19	0.07	0.06	0
27	0.9	2	0.11	0.36	0.38	0.25	0.36	0.18	0.19	0.05	0.05	0
28	0.9	3	0.11	0.11	0.11	0.25	0.09	0.07	0.19	0.04	0.04	0
10	1.5	1	0.09	0.14	0.16	0.50	0.14	0.11	0.33	0.15	0.16	0
18	1.5	1	0.07	0.11	0.12	0.25	0.11	0.06	0.33	0.05	0.06	1
19	1.5	1	0.12	0.12	0.14	0.25	0.10	0.08	0.33	0.05	0.05	0

3. Simulating dust explosions in interconnected vented vessel system

Tests 13, 34 and 33 were simulated with the CFD code DESC 1.0 (see Table 2). The modelling approach, including the empirical model for the coal dust used in the DESC project and the geometry model, has been described previously (Skjold, 2007a). Given the inherent uncertainties associated with the extraction of combustion parameters from standardised tests in 20-litre explosion vessels, the laminar burning velocity S_L derived from the experimental data is modified by introducing a dimensionless multiplication factor C_L, usually set to 1.25 based on experience. The dust poured into the pipe was included as dust layers according to the model described by Skjold *et al.* (2007). Table 2 summarises the simulated scenarios and the main results. Simulations 1-3 are reference simulations for tests 13, 34 and 33, respectively.

Pressure measurements from the commissioning tests suggested that the valves in the dispersion system took about 0.16 seconds to open fully, and this delay was included in the simulations. However, it was not clear how rapidly the energy from the ignition source was released in the experiments, and simulations 4 and 5 explore the effect of varying the ignition delay time for test 13. Since ignition took place in a turbulent flow field, where the still active dispersion system generated mean flow past the ignition location, it is not obvious that the combustion of black powder represented a point like ignition source. Hence, simulations 6-8 explore the effect of moderate variations in the point of ignition for test 13: 0.6 m towards the rear wall (1a), 0.6 m towards the vent opening (1b), and 0.6 m downwards (1c).

Simulations 9-14 investigate the sensitivity of the simulation results with respect to the reactivity of the dust cloud, varied by adjusting the factor C_L from 1.0 to 1.5, with C_L = 1.25 corresponding to the reference simulations (1-3). Finally, simulation 15 explores the effect of refined grid resolution on the results for test 13. In the other simulations the internal geometry was resolved on a cubical grid of size 0.10 m, resulting in a total number of grid cells of 0.73 million. In simulation 15, the internal geometry was resolved on 0.05 m cubical cells, for a total number of grid cells of about 3.5 million.

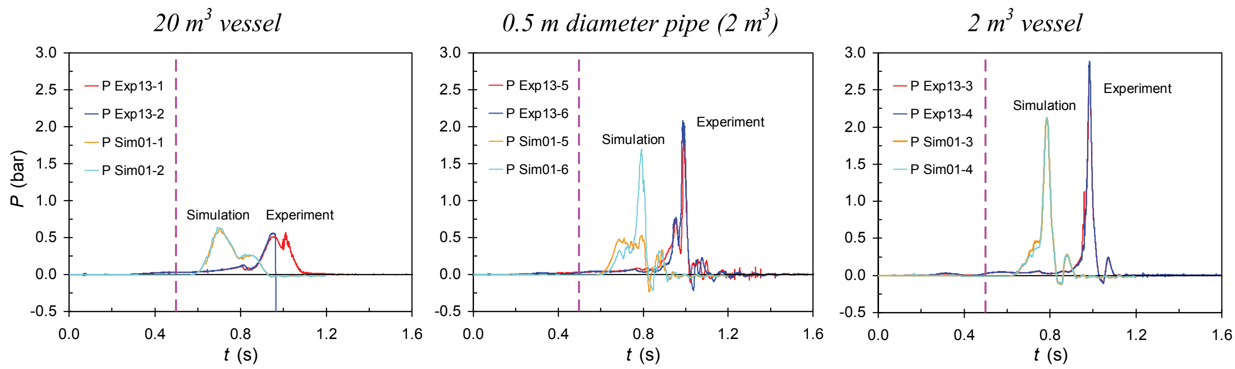
Table 2: Summary of simulations performed with the CFD code DESC.

Sim. No.	**Test No.**	**Ign. Delay**	**Ign. Pos.**	***C_L* Factor**	**Grid** [m]	**20 m³ vessel**		**Connecting pipe**		**2 m³ vessel**	
						P_{CH-1} [bar]	P_{CH-2} [bar]	P_{CH-5} [bar]	P_{CH-6} [bar]	P_{CH-3} [bar]	P_{CH-4} [bar]
1	**13**	0.50	1	1.25	0.10	0.63	0.64	0.53	1.69	**2.12**	**2.13**
2	**34**	0.50	2	1.25	0.10	0.40	0.40	0.48	0.82	0.87	0.87
3	**33**	0.50	3	1.25	0.10	0.60	0.62	1.06	2.24	2.19	2.18
4	13	**0.48**	1	1.25	0.10	0.63	0.64	0.52	1.77	2.18	2.16
5	13	**0.52**	1	1.25	0.10	0.62	0.64	0.57	1.67	2.16	2.16
6	13	0.50	**1a**	1.25	0.10	0.64	0.67	1.36	1.96	**2.85**	**2.86**
7	13	0.50	**1b**	1.25	0.10	0.46	0.49	0.57	1.43	1.31	1.30
8	13	0.50	**1c**	1.25	0.10	0.79	0.80	1.13	2.69	2.33	2.31
9	13	0.50	1	**1.00**	0.10	0.50	0.50	0.47	1.17	1.26	1.25
10	13	0.50	1	**1.50**	0.10	0.79	0.80	1.20	2.37	3.03	3.03
11	34	0.50	2	**1.00**	0.10	0.24	0.25	0.27	0.29	0.63	0.64
12	34	0.50	2	**1.50**	0.10	0.53	0.54	0.88	1.33	1.40	1.41
13	33	0.50	3	**1.00**	0.10	0.39	0.41	0.59	1.21	1.46	1.46
14	33	0.50	3	**1.50**	0.10	0.83	0.84	2.24	2.84	3.07	3.09
15	13	0.50	1	1.25	**0.05**	0.64	0.66	1.28	1.78	2.26	2.24

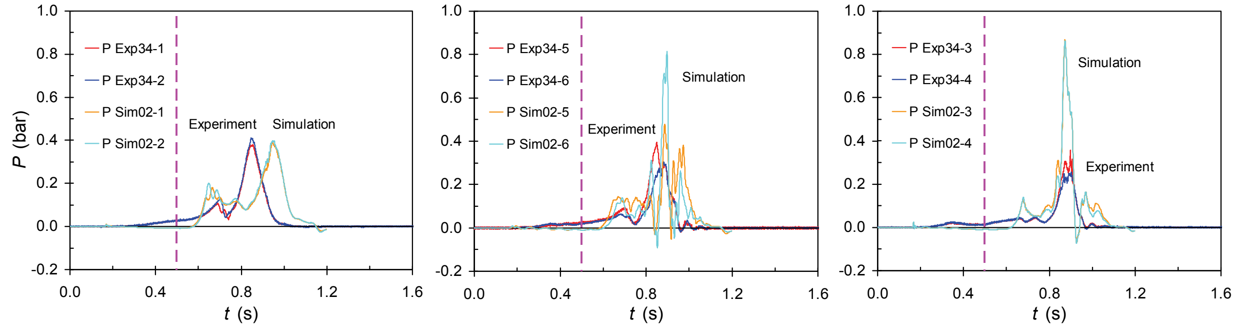
4. Results

Figure 2 summarised the measured pressure-time histories from tests 13, 34 and 33, and the corresponding results from the reference simulations. The simulation results obtained for test 13 are similar results reported in a previous study (Skjold, 2007a), where it was observed that DESC predicted too low pressure enhancement in the secondary vessel. The simulated pressure peaks in the 2 m^3 occur about 0.2 s earlier than in the experiments, and this may be due to uncertainties in the opening time for the dispersion valves, delayed energy release from the ignition source, slow initial rate of combustion in dust clouds under turbulent flow conditions (Dyduch & Skjold, 2010), or inherent limitations in the subgrid models that describe the initial phase of flame propagation in the CFD code.

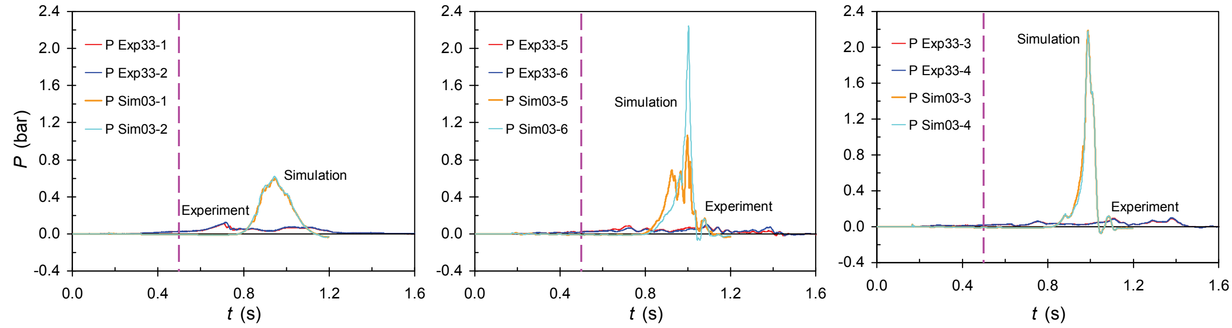
The simulated results for test 34 are in reasonable good agreement with the experiment, although the CFD code predicts pressure enhancement in the secondary vessel that was not measured in the experiment. For test 33 however, with ignition at the side wall in the 20 m^3 vessel, opposite of the entrance to the interconnected vessel, the measured explosion pressure of 0.11 bar is identical to the opening pressure P_{stat} for the vent cover, and much lower than the simulated pressures. Furthermore, it is interesting to note that the explosion propagated to the secondary vessel in this test, and not in test 34. It is not straightforward to explain why test 34, with end ignition, resulted in somewhat lower explosion pressures in the primary vessel compared to tests 13, and it is unfortunate that the repeatability of these experiments could not be explored further during the DESC project.



a) Test no. 13 & Simulation no. 1: ignition in centre of 20 m^3 vessel.



b) Test no. 34 & Simulation no. 2: ignition at rear wall of 20 m^3 vessel.



c) Test no. 33 & Simulation no. 3: ignition at side wall of 20 m^3 vessel.

Figure 2: Measured and simulated pressure-time histories for tests 13, 34 and 33.

Figure 3 summarises the measured signals from the thermocouples for tests 13, 34 and 33, and the simulated temperatures from the corresponding reference simulations. The measured voltages fluctuate less than the simulated temperatures, presumably due to the response time of the thermocouples. The temperature fluctuations seen in the simulations are presumably caused by entrained pockets of air or unreacted mixture in the pipe. No attempt has thus far been made to convert the recorded voltage values to actual temperature measurements in the flow.

The results for simulations 4 and 5 in Table 2 suggest that the effect of varying the ignition delay time is limited for these scenarios, at least within the expected uncertainty in timing originating from the dispersion system and/or the ignition source.

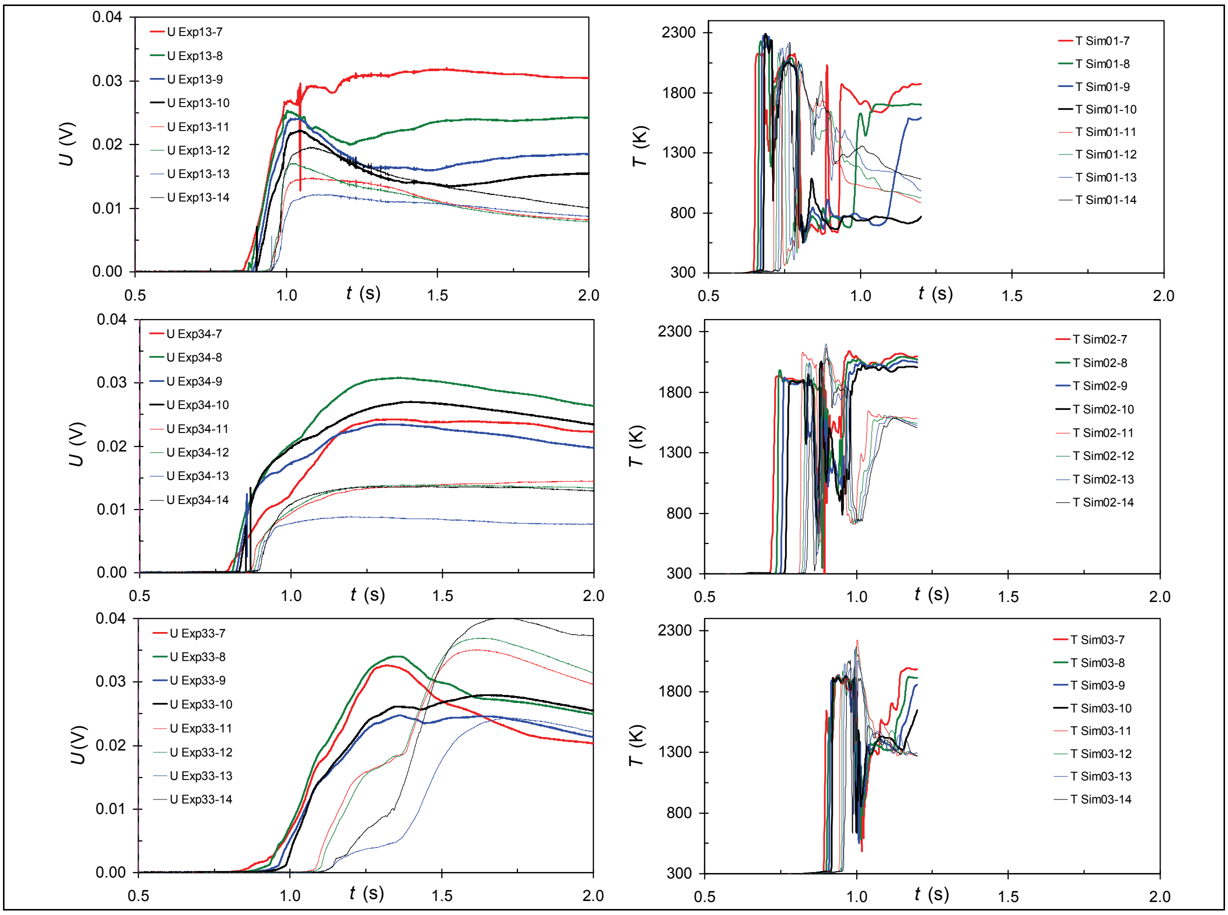


Figure 2: Measured voltages (tests 13, 34 & 33) and simulated temperatures (simulations 1-3).

Figure 3 summarizes the results from simulations 6-8, and illustrate that moderate variations in the location of the ignition source can lead to significantly different explosion pressures. This effect is partly due to the dispersion process, since, at least in the simulations, the dust concentration varies significantly within the 20 m^3 vessel. It is worth nothing that, apart from a 0.2 second time shift in the pressure peaks, the results for simulation 6 are in reasonably good agreement with the experimental results obtained in test 13.

Figure 4 illustrates the effect of varying the reactivity of the dust cloud for the three scenarios. The experimental results are represented by white bars (maximum explosion pressure measured in the 20 m^3 vessel) and black bars (maximum explosion pressure measured in the 2 m^3 vessel), in the respective tests. For all scenarios, an increase in C_L from 1.0 to 1.5 results in roughly a doubling of the simulated explosion pressure in the secondary vessel. For test 13, a C_L value of 1.5 is required to obtain the experimentally observed pressure enhancement in the secondary vessel. However, with this value for C_L the simulation overestimates the explosion pressure in the primary vessel, and the results from simulation 6 show that only a moderate variation in the location of the ignition source may result in similar pressure enhancement.

The results for simulations 1 and 15 in Table 2 suggest a moderate effect of grid resolution.

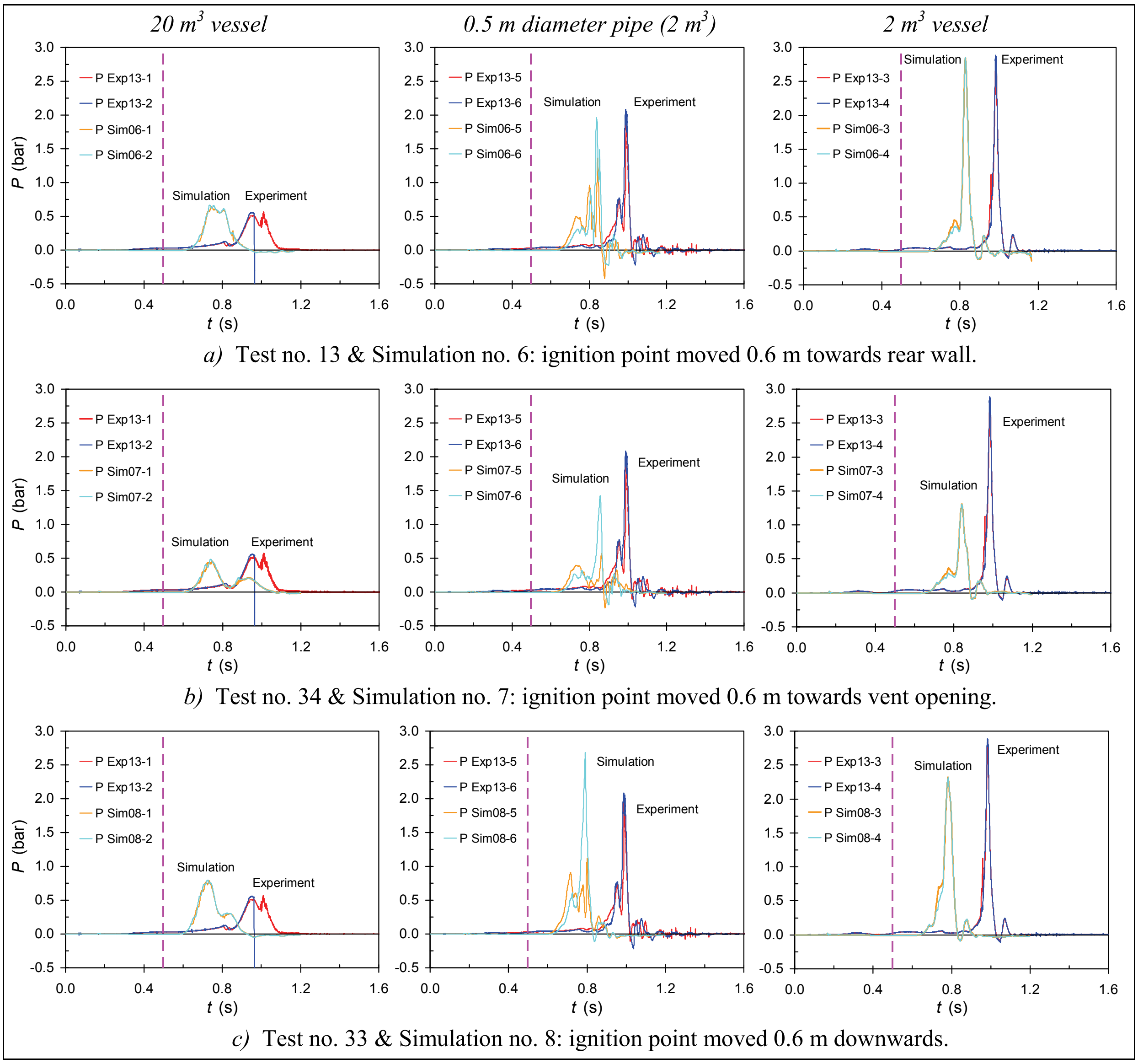


Figure 3: Measured and simulated pressure-time histories for test 13.

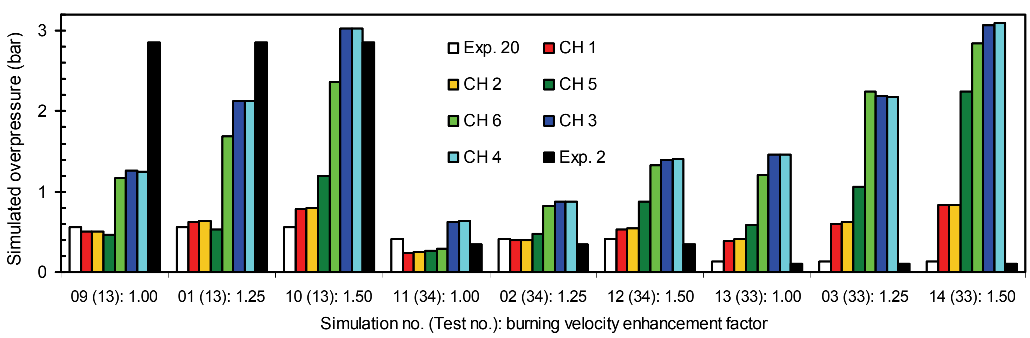


Figure 4: Effect of reactivity on simulated explosion pressures for tests 13, 34 and 33.

5. Discussion and conclusions

The variation in the results from the DESC simulations illustrates some of the challenges associated with the validation of CFD codes for dust explosions. The motivation for developing such codes is to provide a means of predicting the course of flame propagation and pressure build-up in complex systems. However, even for the relatively simple system studied in this example the results are quite sensitive to moderate variations in selected input parameters. This effect can be traced to the physical system, since the ability of the flow from the primary to the secondary vessel to disperse the dust layer inside the pipe has significant effect on the outcome. Without fuel supplied from the pipe, the dust cloud in the secondary vessel will be diluted with the about 2 m^3 of air from the pipe prior to flame arrival. The absence of repeated experiments, as is often seen for large-scale experiments, complicates the situation significantly. Does the measured pressure enhancement in test 13 represents a near worst-case outcome of such an event, for this particular dust, or may the pressure in the 2 m^3 vessel reach even higher values with slightly modified initial and/or boundary conditions?

Some of the modelling uncertainties can be significantly reduced if the experimental procedures are tailored towards model evaluation. For large-scale dust explosion experiments, a few additional experiments may prove most useful for future modelling. If the dispersion system is based on transient release of air and dust from a pressurised reservoir, it is worthwhile to measure the decay of pressure in the reservoirs. This effectively removes the uncertainty associated with the opening time for the valves, and the measured pressure decay can be used directly to derive source terms for release models. High-speed video cameras can record the dispersion process after the nozzle, and such recordings are valuable input to modellers. When chemical igniters or similar strong ignition sources are used, the energy release rate may be estimated by triggering the ignition source inside a constant volume vessel and measuring the pressure. Recordings with high-speed video cameras can also indicate the temporal and spatial extent of the ignition source, although it may be difficult to conduct such tests in realistic flow situations. It is not straightforward to measure dust concentration or turbulence parameters as function of time during the dispersion process, or during dust explosions, but such measurements would obviously be most valuable. Finally, repeat selected tests at least three times!

There are numerous challenges associated with practical consequence assessments for dust explosions in the process industry. Of particular importance for a CFD code that relies on empirical input from standardized dust explosion experiments is the problem of acquiring representative dust samples for testing. In connected vessel systems it is typically the finest fraction of the dust particles that accumulate inside process units, and eventually provide fuel for flame propagation when turbulent flow, shock waves or mechanical vibrations in the walls disperse the accumulated dust layers. Hence, the K_{St} values determined for "as received" samples in the laboratory, typically after drying and sieving, may not be representative for the actual explosion hazard in the plant. On a similar note, the "normal" process conditions in the plant is usually not relevant for risk assessments, since dust explosions rarely occur during normal operation. Hence, the following statement by Bardon & Fletcher (1983) still holds good:

"There remains much to be done before dust explosions are adequately understood".

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