Modelling of industrial dust explosions in complex geometries

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“Causes, severity and mitigation of aerosol and particulate explosions”

Department of Chemical Engineering, Imperial College, London
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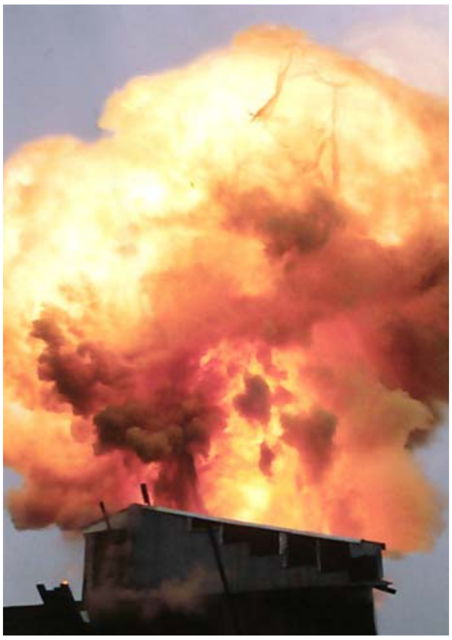
Outline

- Motivation
- The DESC project
- Modelling challenges
- Modelling approach
- Validation work
- Applications
- Conclusions



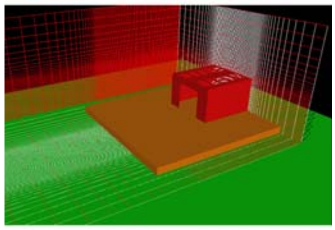
Motivation

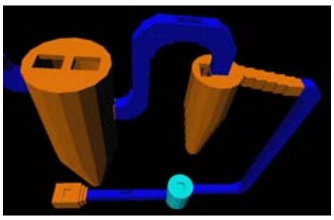
- Dust explosions still occur in the process industry!

Imperial Sugar, Georgia, USA, 8 February 2008: Six casualties!

Motivation

- Numerous empirical guidelines for relatively simple geometries:
  - Venting of silos and isolated vessels, effect of vent ducts, effect of aspect ratio, effect of turbulence, …
- However, not straightforward to extend the “simple guideline approach” to more complex geometries, such as:
  - Mine galleries
  - Interconnected vessel systems
  - Secondary explosions inside buildings
  - …





Motivation

- Computational fluid dynamics (CFD) can take into account:
  - Conservation of mass, momentum and energy!
  - Initial and boundary conditions!

You get something for free; when you use CFD … ☺

- However, the user/developer should decide whether she wants:
  - A model that can provide enlightenment with respect to detailed physical and chemical processes, …

  OR
  - An engineering tool that, for certain types of problems, can provide reasonably accurate predictions for the course of explosions, design loads, escalating explosion scenarios, the effect of various mitigating measures, …

The DESC Project

- **DESC** (Dust Explosion Simulation Code) was a project supported by the European Commission under the Fifth Framework Program – from January 2002 to June 2005
- **Aim**: Develop a commercial CFD-based tool for predicting the consequences of industrial dust explosions in complex geometries!
- **Outcome**: DESC 1.0 released in June 2006 DESC
- **Status**: Some active users, regular "DUG" meetings!
- **Further information**: Paper in JLPPI (Skjold, 2007), …

The DESC Consortium

Partners:

- HSL
- GexCon
- TNO
- FSA
- INBUREX
- Fraunhofer ICT
- Øresund Safety Advisors
- Warsaw University of Technology
- Delft University of Technology
- Lyckeby Culinar
- Hahn & Co

Also involved: INERIS, Fike, University of Bergen, …

Modelling challenges

Dust explosions involve:

– powder technology,

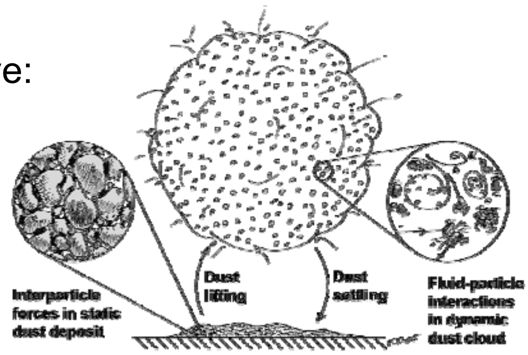
and in particular:

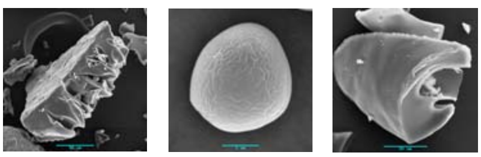
– transient,

– turbulent,

– compressible,

– particle-laden flows!





SEM pictures of 3 different types of potato starch:

Modelling challenges

Dust explosions also involve:

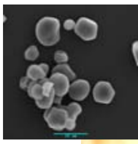
– rapid phase transitions,

– chemical reactions,

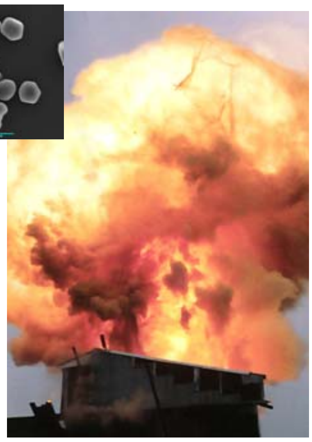
– radiative heat transfer, and

– incomplete combustion of

fuels with largely unknown composition!



SEM picture: Maize starch particles



Maize starch explosion in silo

Modelling challenges

Dust explosions involve:

– industrial-scale,

– primarily internal,

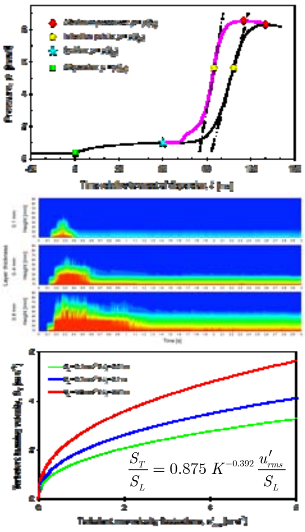
– complex geometries!

The combined effect yields inherently escalating explosion scenarios!

Illustrations: Blaye, 1997
DeBruce, 1998
Imperial Sugar, 2008

Modelling approach in DESC

- ❑ Empirical modelling approach:
  - ❑ Combustion parameters derived from tests in 20-litre explosion vessels
  - ❑ Empirical dust lifting model developed by Warsaw University of Technology
- ❑ “Extreme” use of subgrid models:
  - ❑ Distributed porosity concept for geometry
  - ❑ Standard *k*-ε model with source terms for turbulence production by subgrid objects
  - ❑ Empirical correlation for turbulent burning velocity adopted from gaseous combustion
  - ❑ Equilibrium flow assumption

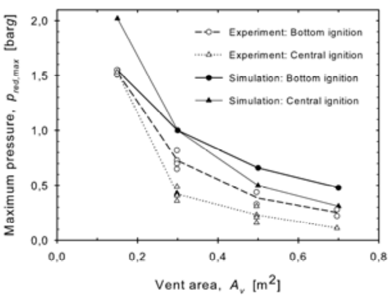


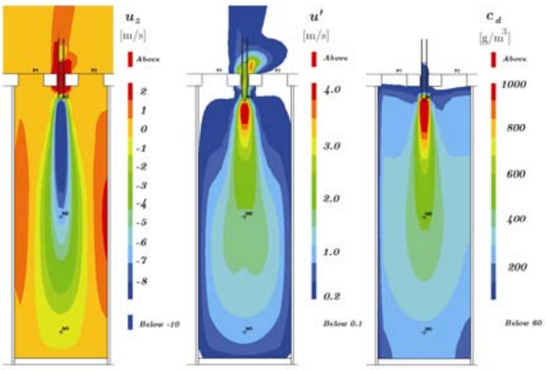
Modelling challenges

- ❑ Simplification
  - ❑ Geometry definition, input parameters, user friendliness, GUIs, …
- ❑ Theoretical foundation
  - ❑ Heterogeneous combustion, combustion regimes, multiphase flow, …
- ❑ Input to empirical models
  - ❑ Relevant experimental data, …
- ❑ Reliable large-scale experiments
  - ❑ Initial and boundary conditions
  - ❑ Measuring relevant parameters: turbulence, dust concentration, …
  - ❑ Experimental uncertainties / repeatability / sensitivity / …

Validation examples

- ❑ DESC simulations of dust explosions in a 9.4 m³ silo
- ❑ Experiments described by Hauert *et al.* (1996)

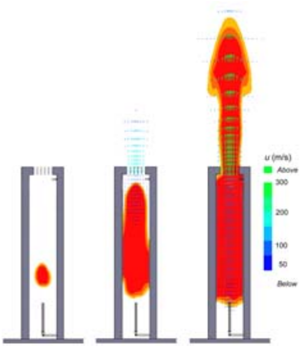




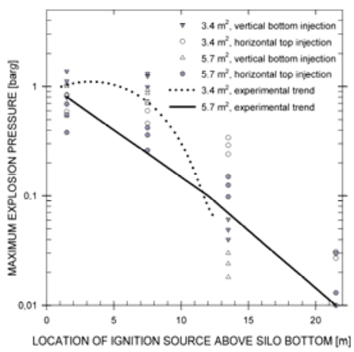
From Skjold *et al.* (2005)

Validation examples

- ❑ DESC simulations of dust explosions in 236 m³ silo
- ❑ Experiments described by Eckhoff *et al.* (1987)

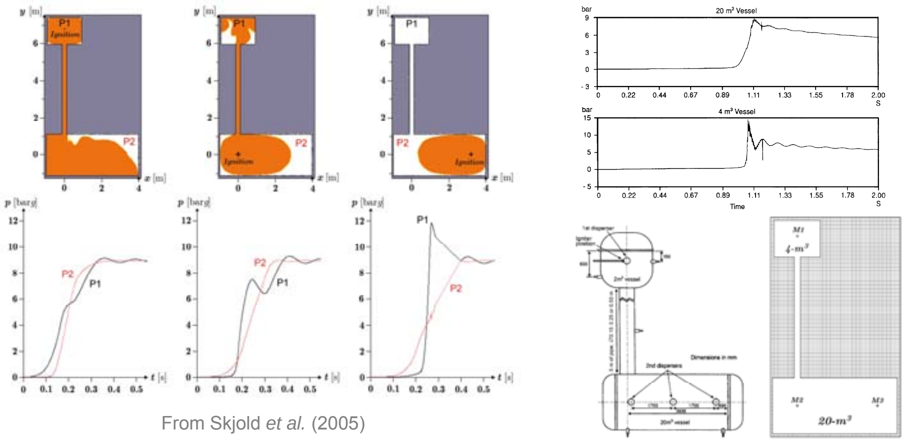


From Skjold *et al.* (2006)



Validation examples

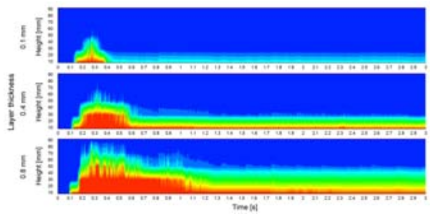
- DESC simulations of connected vessel system
- Experiments described by Lunn *et al.* (1996)

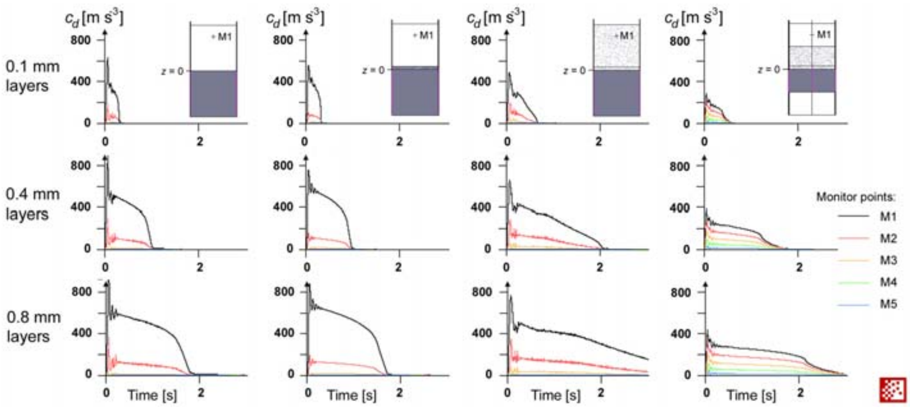


From Skjold *et al.* (2005)

Dust lifting

- Experiment and simulation
- Small scale (Skjold *et al.*, 2007)

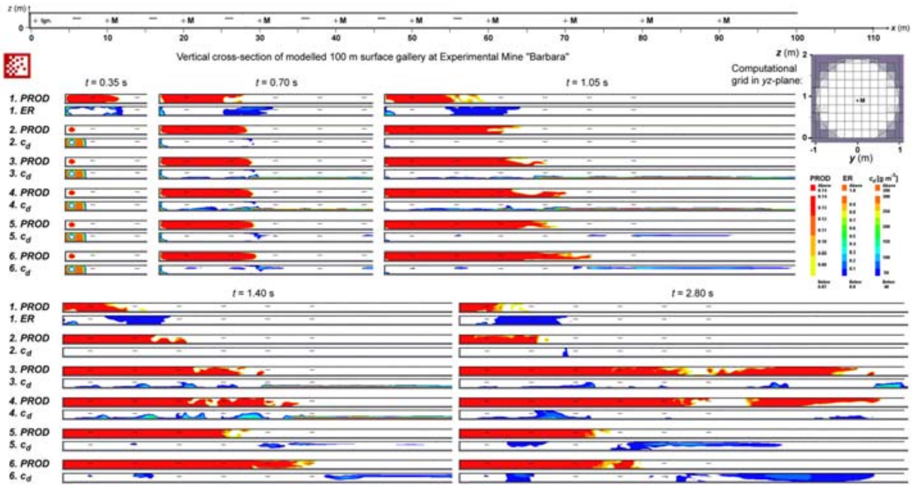




Dust lifting – validation

From Skjold *et al.* (2007)
See also Skjold (2007)

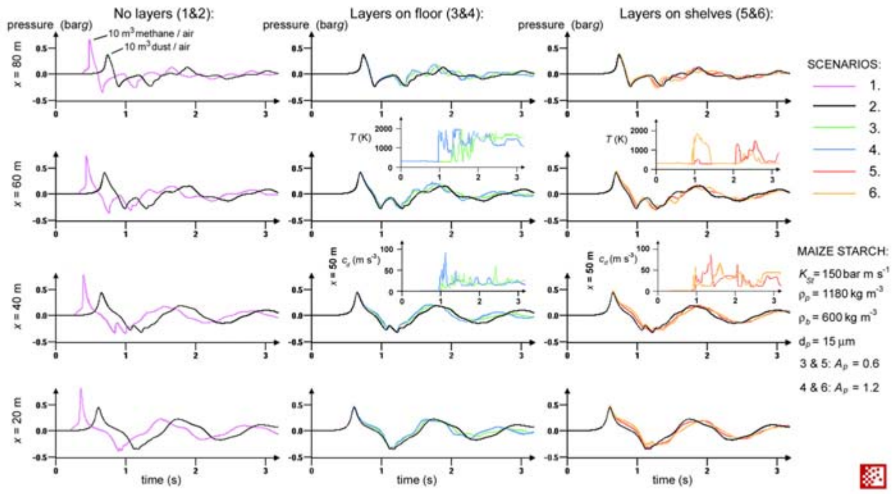
- Simulation of large-scale experiments in 100-m surface gallery at CMI



Dust lifting – validation

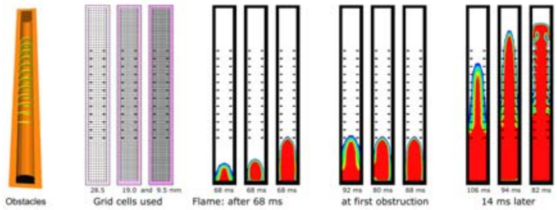
From Skjold *et al.* (2007)
See also Skjold (2007)

- Simulated pressure-time curves in 100-m surface gallery at CMI

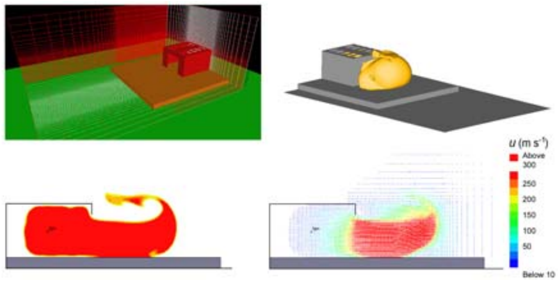


Grid dependence and turbulence

- Flame acceleration tube with repeated obstacles
- Experiments by Pu (1988)
- DESC simulations in Skjold *et al.* (2005)

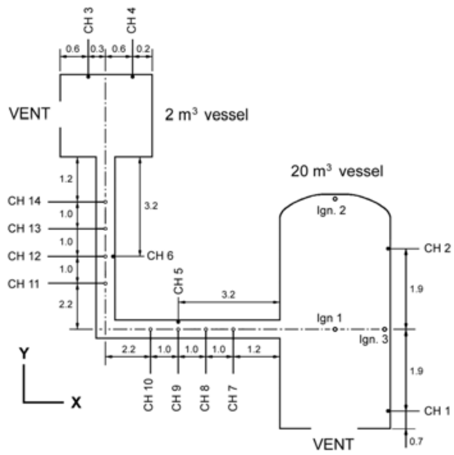


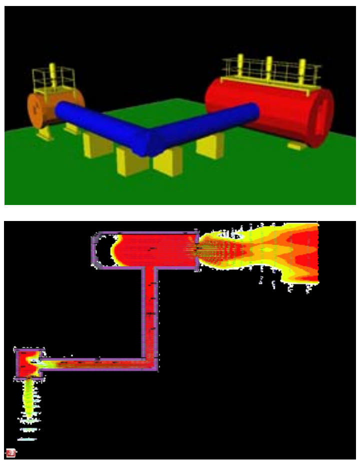
- Effect of initial turbulence
- Experiments described by Tamanini (1990)
- DESC simulations in Skjold *et al.* (2008)
- Relevant for NFPA 68 (Zalosh, 2007)



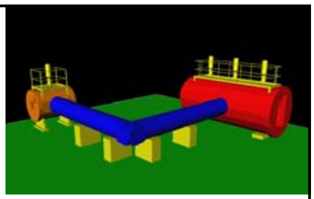
More complex geometries

- Interconnected vented vessel system – HSL





HSL Tests

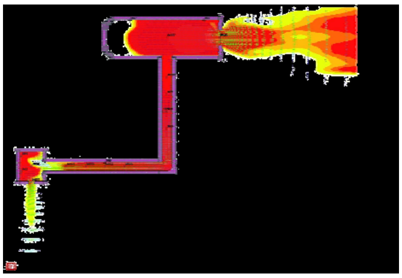


- HSL performed 34 experiments.
- Nine regular tests with coal dust:

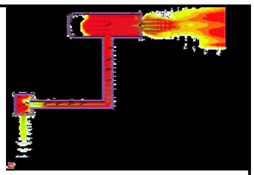
Test No.	20 m³ Vessel					Connecting pipe			2 m³ Vessel			
	A_v [m²]	Ign. pos.	P_{stat} [bar]	P_{CH-1} [bar]	P_{CH-2} [bar]	D_{pipe} [m]	P_{CH-5} [bar]	P_{CH-6} [bar]	A_v [m²]	P_{CH-3} [bar]	P_{CH-4} [bar]	Explo. trans.
13	0.9	1	0.11	0.52	0.56	0.50	1.85	2.10	0.19	2.84	2.86	1
34	0.9	2	0.10	0.38	0.41	0.50	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

DESC Simulations

- Tests 1-3: Performed 15 simulations with DESC 1.0
  - Coal dust model from DESC project
  - Dispersion of dust from reservoirs
  - Opening time for valves estimated
  - Dust layer in connected tube
- Parameter variation:
  - Ignition position
  - Ignition delay
  - Reactivity
  - Grid resolution



Simulations

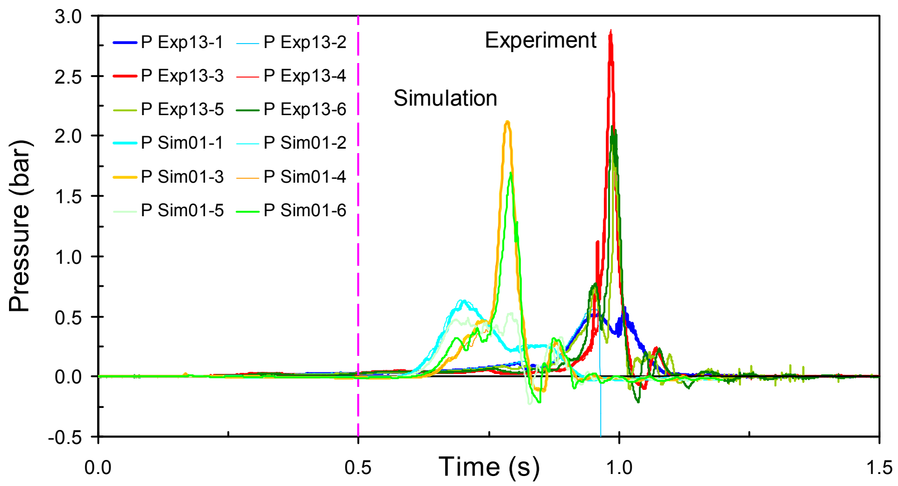


- Three base-case simulations (1-3)
- Variations in delay and position of ignition for test 13

Sim. No.	Test No.	Ign. Delay	Ign. Pos.	C_L Factor	Grid [m]	20 m^3 vessel EXP [bar]	20 m^3 vessel SIM [bar]	Connecting pipe SIM-5 [bar]	Connecting pipe SIM-6 [bar]	2 m^3 vessel EXP [bar]	2 m^3 vessel SIM [bar]
1	13	0.50	1	1.25	0.10	0.54	0.64	0.53	1.69	2.85	2.13
2	34	0.50	2	1.25	0.10	0.40	0.40	0.48	0.82	0.30	0.87
3	33	0.50	3	1.25	0.10	0.12	0.61	1.06	2.24	0.10	2.19
4	13	0.48	1	1.25	0.10	0.54	0.64	0.52	1.77	2.85	2.17
5	13	0.52	1	1.25	0.10		0.63	0.57	1.67		2.16
6	13	0.50	1a	1.25	0.10		0.66	1.36	1.96		2.86
7	13	0.50	1b	1.25	0.10	0.54	0.48	0.57	1.43	2.85	1.31
8	13	0.50	1c	1.25	0.10		0.80	1.13	2.69		2.32

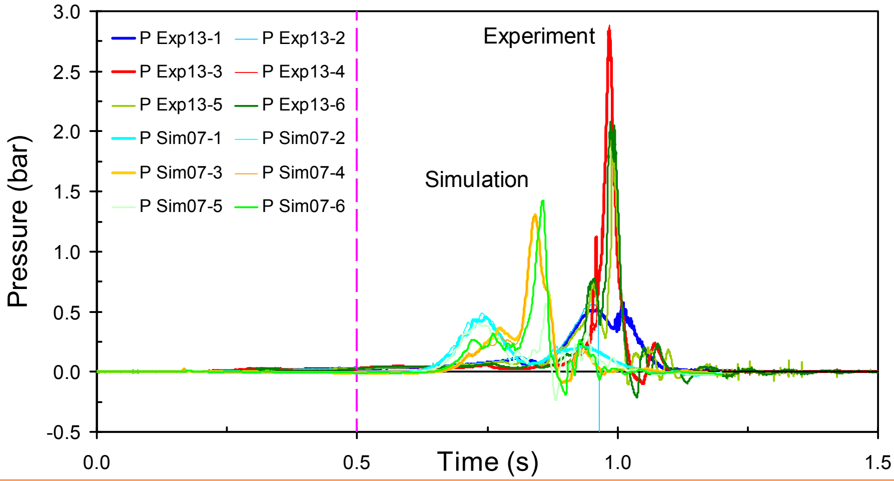
Simulation results – test 13

- Simulation 01: Centre ignition (1) – "base-case": y = 0



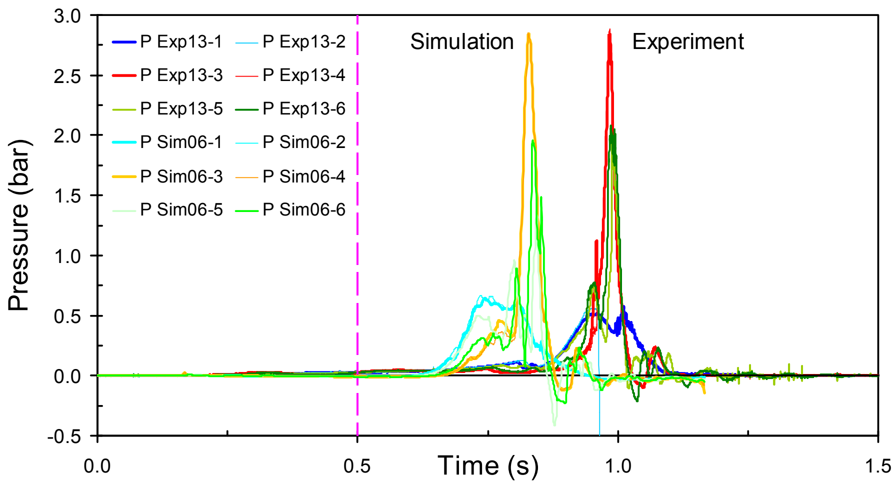
Simulation results – test 13

- Simulation 07: Centre ignition 1b (moved to y = -0.6 m)

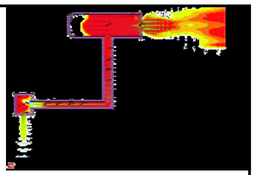


Simulation results – test 13

- Simulation 06: Centre ignition 1a (moved to y = +0.6 m)



Simulations

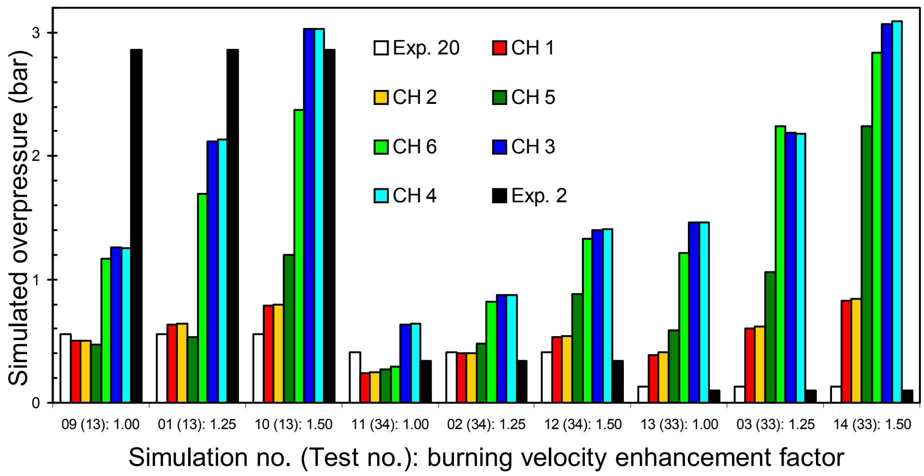


- Variation in reactivity: $S_L = C_L * S_{L,0}$
- Grid resolution for test 13 (base-case simulation)

Sim. No.	Test No.	Ign. Delay	Ign. Pos.	C_L Factor	Grid [m]	20 m^3 vessel EXP [bar]	20 m^3 vessel SIM [bar]	Connecting pipe SIM-5 [bar]	Connecting pipe SIM-6 [bar]	2 m^3 vessel EXP [bar]	2 m^3 vessel SIM [bar]
9	13	0.50	1	1.00	0.10	0.54	0.50	0.47	1.17	2.85	1.26
10	13	0.50	1	1.50	0.10		0.80	1.20	2.37		3.03
11	34	0.50	2	1.00	0.10	0.40	0.25	0.27	0.29	0.30	0.64
12	34	0.50	2	1.50	0.10		0.54	0.88	1.33		1.41
13	33	0.50	3	1.00	0.10	0.12	0.40	0.59	1.21	0.10	1.46
14	33	0.50	3	1.50	0.10		0.84	2.24	2.84		3.08
15	13	0.50	1	1.25	0.05	0.54	0.65	1.28	1.78	2.85	2.25

Simulation results – reactivity

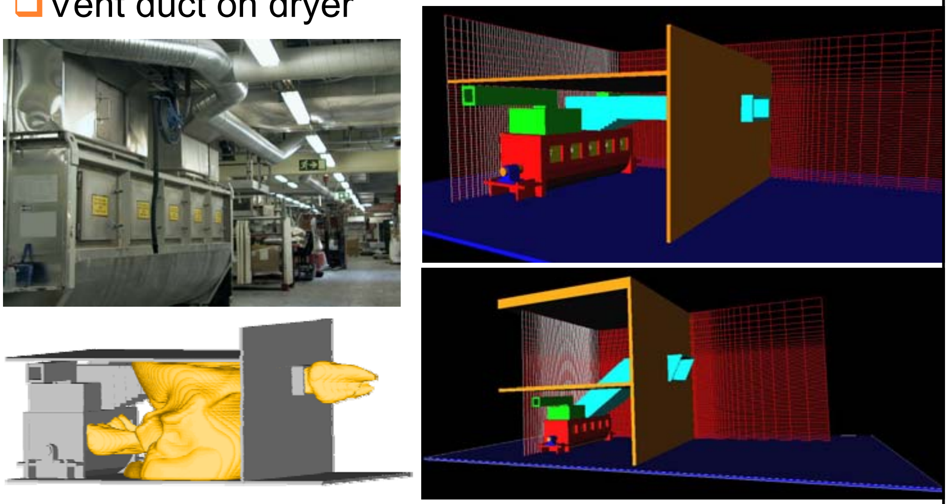
- Effect of varying the burning velocity enhancement factor



DESC applications

- Vent duct on dryer

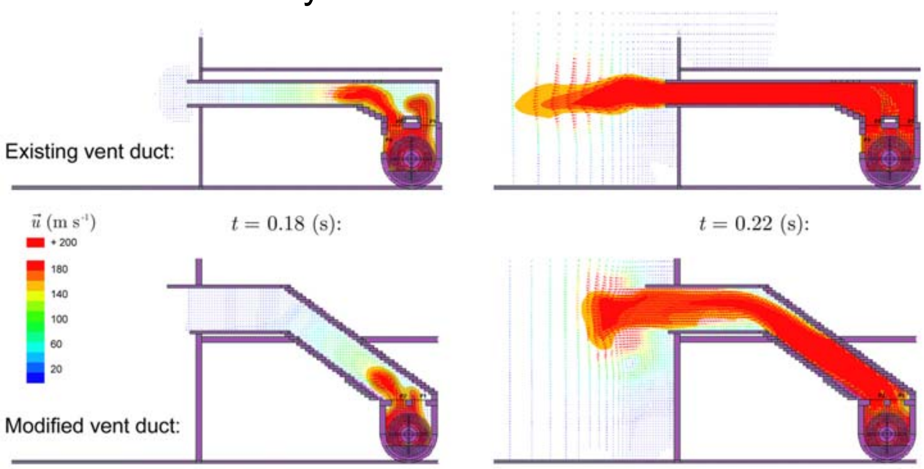
From Skjold *et al.* (2006)



DESC applications

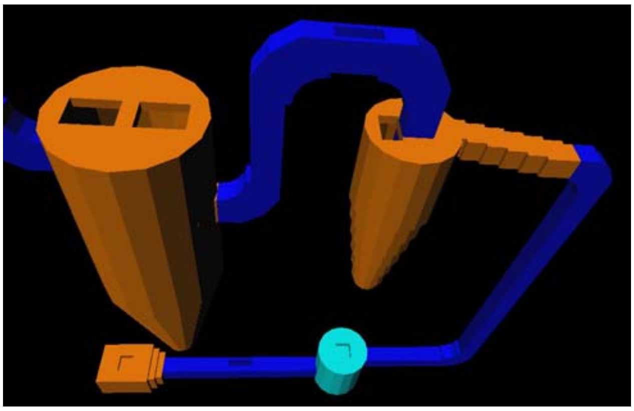
- Vent duct on dryer

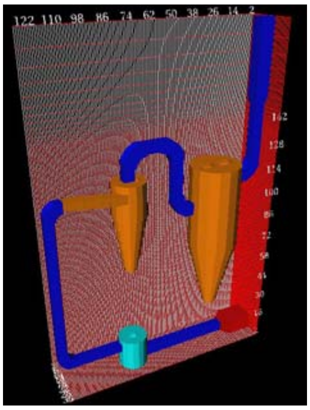
From Skjold *et al.* (2006b)



DESC applications

- Venting of dryer, cyclone, and filter
- Investigating optimal positions for vent openings





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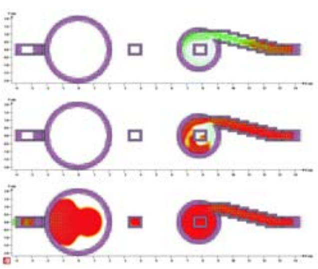
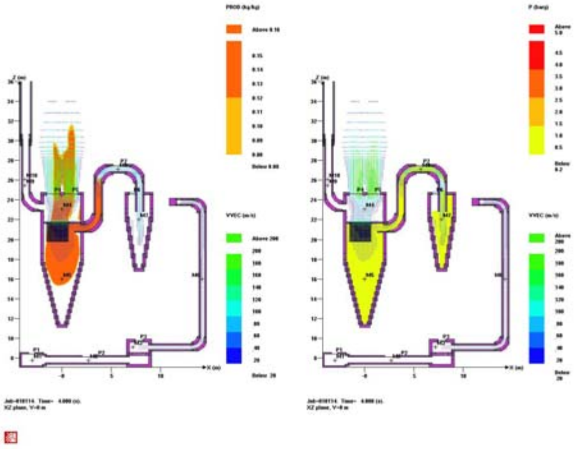
DESC applications

- Venting of dryer, cyclone, and filter





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Conclusions

- Experimental difficulties, limited documentation of experimental conditions, and lack of repeated large-scale tests complicates the validation work!
- The simulation results can be quite sensitive to moderate variations in selected input parameters – even for relatively simple systems!
- For the HSL tests, the sensitivity is closely linked to the dispersion process in the primary vessel and the dust lifting process in the connecting tube!

DESC User Group Meetings

- Informal meetings arranged approximately once every year.
- Focus on models improvements, experiments & user guidelines!
- The Fifth DUG meeting will be hosted by Central Mining Institute at Experimental Mine "Barbara“ in Poland, 14-15 October 2010.

“There remains much to be done before dust explosions are adequately understood”

Bardon & Fletcher (1983)

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