Modelling of industrial dust explosions in complex geometries

Trygve Skjold
Manager GexCon R&D

Forty-sixth UKELG one-day discussion meeting on “Causes, severity and mitigation of aerosol and particulate explosions”
Department of Chemical Engineering, Imperial College, London
Wednesday 22 September 2010

Outline

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

- Dust explosions still occur in the process industry!

- 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!

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

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

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!

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 $k-\varepsilon$ 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

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

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

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$A_i$ [m$^2$]</th>
<th>Ign. pos.</th>
<th>$P_{tot}$ [bar]</th>
<th>$P_{CH-1}$ [bar]</th>
<th>$P_{CH-2}$ [bar]</th>
<th>$P_{CH-3}$ [bar]</th>
<th>$P_{CH-4}$ [bar]</th>
<th>$P_{CH-5}$ [bar]</th>
<th>$P_{CH-6}$ [bar]</th>
<th>Explo. trans.</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0.9</td>
<td>1</td>
<td>0.11</td>
<td>0.52</td>
<td>0.56</td>
<td>0.50</td>
<td>1.85</td>
<td>2.10</td>
<td>0.19</td>
<td>2.84</td>
</tr>
<tr>
<td>34</td>
<td>0.9</td>
<td>2</td>
<td>0.10</td>
<td>0.38</td>
<td>0.41</td>
<td>0.50</td>
<td>0.39</td>
<td>0.30</td>
<td>0.19</td>
<td>0.34</td>
</tr>
<tr>
<td>33</td>
<td>0.9</td>
<td>3</td>
<td>0.11</td>
<td>0.11</td>
<td>0.13</td>
<td>0.50</td>
<td>0.09</td>
<td>0.10</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>22</td>
<td>0.9</td>
<td>1</td>
<td>0.09</td>
<td>0.35</td>
<td>0.38</td>
<td>0.25</td>
<td>0.28</td>
<td>0.16</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>27</td>
<td>0.9</td>
<td>2</td>
<td>0.11</td>
<td>0.36</td>
<td>0.38</td>
<td>0.25</td>
<td>0.36</td>
<td>0.18</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>28</td>
<td>0.9</td>
<td>3</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.25</td>
<td>0.09</td>
<td>0.07</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>10</td>
<td>1.5</td>
<td>1</td>
<td>0.09</td>
<td>0.14</td>
<td>0.16</td>
<td>0.50</td>
<td>0.14</td>
<td>0.11</td>
<td>0.33</td>
<td>0.15</td>
</tr>
<tr>
<td>18</td>
<td>1.5</td>
<td>1</td>
<td>0.07</td>
<td>0.11</td>
<td>0.12</td>
<td>0.25</td>
<td>0.11</td>
<td>0.06</td>
<td>0.33</td>
<td>0.05</td>
</tr>
<tr>
<td>19</td>
<td>1.5</td>
<td>1</td>
<td>0.12</td>
<td>0.12</td>
<td>0.14</td>
<td>0.25</td>
<td>0.10</td>
<td>0.08</td>
<td>0.33</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Sim. No.</th>
<th>Test No.</th>
<th>Ign. Delay</th>
<th>Ign. Pos.</th>
<th>$C_z$ Factor</th>
<th>Grid [m]</th>
<th>20 m$^3$ vessel</th>
<th>Connecting pipe</th>
<th>2 m$^3$ vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EXP [bar]</td>
<td>SIM [bar]</td>
<td>SIM [bar]</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>0.50</td>
<td>1</td>
<td>1.25</td>
<td>0.10</td>
<td>0.54</td>
<td>0.64</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>0.50</td>
<td>2</td>
<td>1.25</td>
<td>0.10</td>
<td>0.40</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>0.50</td>
<td>3</td>
<td>1.25</td>
<td>0.10</td>
<td>0.12</td>
<td>0.61</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>0.48</td>
<td>1</td>
<td>1.25</td>
<td>0.10</td>
<td>0.54</td>
<td>0.64</td>
<td>0.52</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>0.52</td>
<td>1</td>
<td>1.25</td>
<td>0.10</td>
<td>0.40</td>
<td>0.63</td>
<td>0.57</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>0.50</td>
<td>1a</td>
<td>1.25</td>
<td>0.10</td>
<td>0.66</td>
<td>1.36</td>
<td>1.96</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>0.50</td>
<td>1b</td>
<td>1.25</td>
<td>0.10</td>
<td>0.54</td>
<td>0.48</td>
<td>0.57</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>0.50</td>
<td>1c</td>
<td>1.25</td>
<td>0.10</td>
<td>0.80</td>
<td>1.13</td>
<td>2.69</td>
</tr>
</tbody>
</table>

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

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

### Simulation results – reactivity

- Effect of varying the burning velocity enhancement factor

<table>
<thead>
<tr>
<th>Sim. No.</th>
<th>Test No.</th>
<th>Ign. Delay</th>
<th>Ign. Pos.</th>
<th>( C_L ) Factor</th>
<th>Grid [m]</th>
<th>20 m³ vessel</th>
<th>Connecting pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EXP [bar]</td>
<td>SIM [bar]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SIM-5 [bar]</td>
<td>SIM-6 [bar]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EXP [bar]</td>
<td>SIM [bar]</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>0.50</td>
<td>1</td>
<td>1.00</td>
<td>0.10</td>
<td>0.54</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td>1.17</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
<td>0.50</td>
<td>1</td>
<td>1.50</td>
<td>0.10</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.80</td>
<td>2.37</td>
</tr>
<tr>
<td>11</td>
<td>34</td>
<td>0.50</td>
<td>2</td>
<td>1.00</td>
<td>0.10</td>
<td>0.40</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>12</td>
<td>34</td>
<td>0.50</td>
<td>2</td>
<td>1.50</td>
<td>0.10</td>
<td>0.54</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.54</td>
<td>1.33</td>
</tr>
<tr>
<td>13</td>
<td>33</td>
<td>0.50</td>
<td>3</td>
<td>1.00</td>
<td>0.10</td>
<td>0.12</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td>0.59</td>
</tr>
<tr>
<td>14</td>
<td>33</td>
<td>0.50</td>
<td>3</td>
<td>1.50</td>
<td>0.10</td>
<td>0.84</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.84</td>
<td>2.84</td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>0.50</td>
<td>1</td>
<td>1.25</td>
<td>0.05</td>
<td>0.54</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Forty-sixth UKELG Meeting – Wednesday 22 September 2010 – Imperial College, London
DESC applications

- Vent duct on dryer

From Skjold et al. (2006)

- Vent duct on dryer

From Skjold et al. (2006b)
DESC applications

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

References

References


References


Bibliography

Bibliography