CFD Lagrangian Multiphase Simulation Applied to Dust Explosion Characterization

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1. Introduction to dust explosions
2. Explosivity Parameters and Equipment
3. Simulation
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1. Introduction to dust explosions: Imperial Sugar Case

**Place:** Port Wentworth, Georgia, USA

**Date:** February 7, 2008.

**Process:** Sugar refinery.

**Combustible:** Sugar.

Mean Particle size (μm): 23

\[ P_{\text{max}} \text{ (bar)}: 7.5 \]

\[ \text{MEC (g/m}^3\text{): 95} \]

\[ \text{Kst (bar m/s): 139} \]

**Impact:**

- 14 fatalities.
- 36 injured.
- Process plant total destruction.

Vorderbrueggen (2011)
1. Introduction to dust explosions

Eckhoff (2009)
1. Introduction to dust explosions
2. Explosivity parameters: Maximum pressure and maximum rate of pressure rise

Typical pressure profile of an explosion on the 20 L Sphere

Dahoe et al. (2001)
2. Explosivity parameters: Minimum Explosivity Concentration (MEC)

Maize Starch Characterization

Eckhoff (2009)
2. Explosivity parameters:
Particle Size

Aluminium Dust in Air

Eckhoff (2009)
2. Explosivity parameters:

**Turbulence level**

*Graph showing the relationship between delay between dust dispersion and ignition and the maximum rate of pressure change (dP/dt) max in Lycopodium in Air. Diagram from Eckhoff (2009).*
2. Explosivity parameters: Deflagration Index

\[ K_{st} = \left( \frac{dP}{dt} \right) V^{1/3} \]

Is a severity index developed from the maximum rate of pressure rise and volume-invariant.

Table 1. Risk level associated to Deflagration Index

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>( K_{st} ) (bar m/s)</th>
<th>Explosion Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 1</td>
<td>1-200</td>
<td>Weak</td>
</tr>
<tr>
<td>ST 2</td>
<td>201-300</td>
<td>Strong</td>
</tr>
<tr>
<td>ST 3</td>
<td>&gt; 300</td>
<td>Very Strong</td>
</tr>
</tbody>
</table>
2. Explosivity parameters: Deflagration Index

\[ K_{st} = \left( \frac{dP}{dt} \right) V^{1/3} \]

Is a severity index developed from the maximum rate of pressure rise and volume-invariant.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean Particle Size</th>
<th>Concentration</th>
<th>K_{st} (bar m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td>10</td>
<td>105</td>
<td>189</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>63</td>
<td>25</td>
<td>267</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>40</td>
<td>50</td>
<td>165</td>
</tr>
</tbody>
</table>
2. Dust explosion characterization equipment

- MEC from nominal concentration.
- Maximum pressure ($P_{\text{max}}$).
- Maximum rate of pressure rise ($dP/dt_{\text{max}}$).
2. Deflagration Index

\[ K_{st} = \left( \frac{dP}{dt} \right)^{V^{1/3}} \]

Dahoe et al. (2001)
2. Dust explosion characterization equipment: Comparative Table

Table 2. Comparison between dust explosion characterization equipments

<table>
<thead>
<tr>
<th></th>
<th>20 L Sphere</th>
<th>1 m³ Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust container pressure (barg)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Ignition Time (ms)</strong></td>
<td><strong>60</strong></td>
<td><strong>200</strong></td>
</tr>
<tr>
<td>Ignition Energy (kJ)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Type of nozzle</td>
<td>Rebound</td>
<td>Annular</td>
</tr>
<tr>
<td>Type of flammable dust</td>
<td>High densities</td>
<td>All densities</td>
</tr>
</tbody>
</table>
2. Experimental Studies

Dahoe et al. (2001)
3. Objectives

• To develop a CFD multiphase flow to evaluate the dispersion phenomena of flammable dust within the 20 L Sphere under standard test conditions.

• To evaluate the dust concentration at ignition point on the moments previous to the explosion.

• To evaluate the turbulence level during the dispersion of the dust.

• To evaluate the particle distribution within the domain taking into account the particle size.
3. Simulation: General Geometry

- Igniters
- Sphere
- Nozzle
- Canister
- Nozzle Vertical Cut
3. Simulation: Mesh

Models:
- Polyhedral mesher
- Advancing Layer Mesher
- Surface Remesher

Principal Reference Values:
- Number prism layers: 2
- Prism Layer Thickness: 0.036 mm
- Minimum Surface Size: 0.2 mm

Mesh Results:
- Cells: 7,316,852
- Faces: 51,224,435
- Verts: 43,619,275
3. Simulation: Mesh

Vel_{ref} > 400 m/s
3. Simulation: Principal Models

- Implicit Unsteady.
  - Time Step: 1 ms
  - Temporal Discretization: 2\textsuperscript{nd} Order

- Compressible Gas: Peng-Robinson

- Lagrangian Multiphase

- Detached Eddy Simulation
3. Simulation: Principal Models

• Lagrangian Multiphase:
  – Material: Starch
  – Models:
    • Constant density: \( \rho = 610 \text{ kg/m}^3 \)
    • Drag Force
    • Material Particles
    • Pressure Gradient Force
    • Spherical Particles

• Injector:
  – Mass Flow Rate: 6 kg/s for \( t < 0.2 \text{ ms} \)
  – Number of Parcels: \( 2.2 \times 10^6 \)
  – Particle Size Distribution from laser diffraction (Table 3)

Table 3. Particle Size Distribution from laser diffraction

![Particle Size Distribution Graph](image)
3. Simulation: Initial Conditions
4. Results: Influence of iterations
4. Results: Computational cost

- Windows Server 2008 – 64-bit
- Processor: Intel® Xeon® X5060 @ 2.67GHz
- RAM; 40 Gb
4. Results:
Particle flow
4. Results:
Particle flow
4. Results:
Particle diameter for 1000 iter

1 ms

Particle Diameter (m)

1.7925e-05  2.8977e-05  4.0029e-05  5.1081e-05  6.2133e-05  7.3186e-05
5. Conclusions

- **STAR-CCM+®** was used to developed a **multiphase lagrangian** flow in order to simulate the flammable dust dispersion within the 20 L sphere.
- The number of **Maximum Inner Iterations** has a significant impact on the results as well as on the **computational cost**.
- The **nozzle disperses correctly** the dust within the domain. However, the **smaller particles tends to the walls** and the bigger ones to the center of the sphere.
- In order to model correctly the behavior of the flow, and due to the **geometry high complexity**, it was necessary to implement the **DES turbulence model**.
5. Future Work

- The Maximum Inner Iterations will be increased to 1500.

- The simulation time will be 120 ms in order to evaluate a better ignition time for the standard test.

- The use of cohesion models to represent particle fragmentation and agglomeration will be added.

- Another types of nozzle will be simulated in order to evaluate the dust homogeneity within the sphere.
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W. Bartknecht, "Explosions and how they may be prevented," 1978.


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