Stefano Chiti

A PILOT STUDY ON HYPOXIC AIR PERFORMANCE AT THE INTERFACE OF FIRE PREVENTION AND FIRE SUPPRESSION

FireSEAT 2011 – The Science of Suppression

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• What is Hypoxic Air Technology (HAT)?
• Effects of low $O_2$ concentration on the ignition and combustion processes.
• Ignition property test method.
• Flame spread test method.
• Results and discussion of the test series to assess the performance of hypoxic air.
• Conclusions and future development.
Hypoxic Air Technology (HAT): what is it?

**Hypoxic Air Technology:**
- Fire prevention technology based on a continuous reduction of O\textsubscript{2} in the protected volumes.
- When even fire suppression is not acceptable.
- Typically 14-15 vol% O\textsubscript{2}, 85-84 vol% N\textsubscript{2} for fire prevention.
- Lower O\textsubscript{2} concentrations for fire suppression (consistent with gas extinguishing systems).
**Minimum Oxygen Concentration (MOC) : below MOC no combustion**

- depends on the diluent used to reduce O$_2$
- if diluent is N$_2$ : \[ MOC = LFL \cdot \frac{1}{4.77} \cdot \left( \frac{100}{C_{st}} - 1 \right) \]
  - where LFL is the Lower Flammable Limit, $C_{st}$ is the stoichiometric oxygen/fuel concentration
- similar relationship also for dust clouds
- MOC for fire prevention is not the same as for fire suppression
Effects of low O$_2$ concentration on ignition and combustion

- **Ignition time: increases when lowering O$_2$ concentration**
  - Mc. Alevy et. al.: $t_{ign} \propto m_{O_2}^{-2/3}$
  - Kumar and Hermance: $t_{ign} \propto m_{O_2}^{-n}$
  - Mikkola, Hirsch, Hsieh:
    - PVC: +300% ignition time in O$_2$= 15 vol%
    - PMMA: + 24% ignition time in O$_2$= 15 vol%
    - Silicone elastomers: drastic increase
    - FR PUR foam: drastic increase
    - But it is not investigated what happens after ignition
Autoignition time (AIT): increases when lowering \( O_2 \) concentration

- Kashiwagi: 15 vol% limiting \( O_2 \) value for successful autoignition
- Experiments on AIT for gases:  \[ AIT = \frac{e^{E/RT}}{[O_2]^n} \]
- Alvares:  \( AIT \propto P_{O_2}^{-0.25} \)

Minimum Ignition Energy (MIE): rises when decreasing \( O_2 \) concentration

- Experiment on gases:  \( MIE \propto OI^{-n} \)
  - where Oxygen Index \( OI = O_2/(O_2 + N_2) \); \( n = 4 \) (Chinn) or \( n = 2.5 \) (Von Elbe)
Effects of low $O_2$ concentration on ignition and combustion

- **Flame spread velocity ($V$): decreases at low $O_2$ concentrations**
  - Studies reported by Babrauskas: $V \propto m_{O_2}^n$
    - where $n = 2$ or $n = 1$

- **Mass loss rate (MLR): decreases at low $O_2$ concentrations**
  - Santo and Tewarson: MLR - 30% in $O_2 = 18$ vol% (PMMA)
  - Babrauskas reports: $MLR'' = a \cdot m_{oxygen} - b$
    - where $MLR''$ is the MLR per unit of surface area, $a$ and $b$ are constant

- **Heat release rate (HRR): decreases drastically if $O_2$ concentration is low**
  - Mulholland: The heat peak decreases drastically if $O_2$ is lowered, and this effect is greater when approaching the lowest $O_2$ concentration at which combustion can be sustained.
Effects of low O$_2$ concentration on ignition and combustion - discussion

- Hypoxic air, by lowering O$_2$ concentration in the air, has several benefits regarding to the ignition and combustion processes:
  - longer ignition time
  - higher MIE
  - lower flame spread velocity
  - reduced MLR

- Oxygen concentration $\leq$ 15vol% can prevent ignition for most solid materials (hypoxic air for fire prevention).

- Oxygen concentration must be consistent with the values for gas suppression systems if hypoxic air is used in suppression mode ($O_2 = 12$–13 vol%).
Test method to assess hypoxic air performance – aim

1. Investigate the ignition limiting properties of hypoxic air for fire prevention for different material configurations.

2. Investigate fire spread at different O$_2$ concentrations (vertical material configuration - worst case).
Test method to assess hypoxic air performance – test room

- $V = 10.35 \, m^3$
- $H = 2.3 \, m$
- **Airtight room with adjoining air lock**
- Door and observation windows.
- Smoke extractor fan
Test method to assess hypoxic air performance – equipment

- Nitrogen generator.
- O\textsubscript{2} sensors.
- Oxyacetylene premixed pilot flame.
- Calibrated scale.
- Support frame.
- Common specimens.
Ignition test - procedure

1. Horizontal/vertical arrangement of the test specimen, flame direction.

2. Reduce $O_2$ concentration in the test room ($O_2$ constant throughout the test)

3. Regulate pilot flame.

4. The pilot flame hit the test specimen for 180 s (FET, Flame Exposure Time).

5. Remove the pilot flame and observe the test specimen response for at least 60 s (PET, Post Exposure Time).

- Data on test specimen mass, $O_2$ concentration are continuously recorded during FET and PET.
- Consistent with BSI PAS 95, VdS 3527
Flame spread test - procedure

1. Vertical array of test specimens.
2. Reduce $O_2$ concentration in the test room.
3. Regulate pilot flame.
4. The pilot flame hit the bottom test specimen for 180 s.
5. Observe if flames spread to the other two specimens.

- Data on test specimens mass, $O_2$ concentration continuously recorded.
Ignition test – results

- **Polypropylene (PP): horizontal configuration test.**
  - Test specimen: PP box (37x25x12 cm)
  - Ignition limiting $O_2$ threshold: 16.0 vol% (VdS 3527)

<table>
<thead>
<tr>
<th>$O_2$ (vol%)</th>
<th>Ignition during FET</th>
<th>Self-sustained burning/flame spread during PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>17.9</td>
<td>YES</td>
<td>Small flames, self-extinguishing after 20 s</td>
</tr>
<tr>
<td>20.9</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
Ignition test – results

- Polypropylene (PP) : vertical configuration test.
  - Test specimen: PP lid for box

<table>
<thead>
<tr>
<th></th>
<th>Ignition during FET</th>
<th>Self-sustained burning/flame spread during PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2 = 14.9 \text{ vol}%$</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>$O_2 = 17.0 \text{ vol}%$</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>$O_2 = 20.9 \text{ vol}%$</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

![Graph showing mass loss over time for different oxygen concentrations](#)
Ignition test – results

- **Paper: horizontal configuration test.**
  - Test specimen: rolled newspaper
  - Ignition limiting $O_2$ threshold: 14.1 vol\%

<table>
<thead>
<tr>
<th>$O_2$ (vol%)</th>
<th>Ignition during FET</th>
<th>Self-sustained burning/flame spread during PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.9</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>17.0</td>
<td>YES</td>
<td>Pyrolyzing fire</td>
</tr>
<tr>
<td>18.0</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>20.9</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
Ignition test – results

- **ISO wood crib: horizontal configuration test.**
  - Test specimen: ISO wood crib, mini crib type, 5 layers each crib, 2 members each layer, total volume 78 cm³.
  - Test specimen moistened with pure alcohol.
  - Ignition limiting O₂ threshold: 17.0 vol% (untreated wood, VdS 3527)

<table>
<thead>
<tr>
<th>O₂ (vol%)</th>
<th>Ignition during FET</th>
<th>Self-sustained burning/flame spread during PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.9</td>
<td>YES</td>
<td>Small flames, self-extinguishing after 10 seconds.</td>
</tr>
<tr>
<td>16.0</td>
<td>YES</td>
<td>Small flames, self-extinguishing after 120 seconds.</td>
</tr>
<tr>
<td>17.0</td>
<td>YES</td>
<td>Flames, self-extinguishing after 180 seconds.</td>
</tr>
<tr>
<td>18.0</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>19.0</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>20.0</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>20.9</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
## Ignition test – results

<table>
<thead>
<tr>
<th>Initial mass</th>
<th>Mass lost during FET</th>
<th>Mass lost during PET</th>
<th>Mass loss during FET+PET</th>
<th>Final mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2 = 14.9\ \text{vol}%$</td>
<td>16.9 g</td>
<td>13.61 %</td>
<td>2.37 %</td>
<td>15.98 %</td>
</tr>
<tr>
<td>$O_2 = 16.0\ \text{vol}%$</td>
<td>16.9 g</td>
<td>14.20 %</td>
<td>27.81 %</td>
<td>42.01 %</td>
</tr>
<tr>
<td>$O_2 = 17.0\ \text{vol}%$</td>
<td>16.9 g</td>
<td>16.57 %</td>
<td>55.03 %</td>
<td>71.60 %</td>
</tr>
<tr>
<td>$O_2 = 18.0\ \text{vol}%$</td>
<td>16.9 g</td>
<td>14.20 %</td>
<td>77.51 %</td>
<td>91.71 %</td>
</tr>
<tr>
<td>$O_2 = 19.0\ \text{vol}%$</td>
<td>16.7 g</td>
<td>-----</td>
<td>-----</td>
<td>96.41 %</td>
</tr>
<tr>
<td>$O_2 = 20.0\ \text{vol}%$</td>
<td>16.8 g</td>
<td>-----</td>
<td>-----</td>
<td>97.62 %</td>
</tr>
<tr>
<td>$O_2 = 20.9\ \text{vol}%$</td>
<td>16.6 g</td>
<td>-----</td>
<td>-----</td>
<td>100 %</td>
</tr>
</tbody>
</table>

Before test $O_2 = 15.0 \text{ vol}\%$  $O_2 = 16.0 \text{ vol}\%$  $O_2 = 17.0 \text{ vol}\%$
Ignition test – an example

$O_2 = 14.9 \text{ vol}\%$

$O_2 = 20.9 \text{ vol}\%$
Fire spread test - results

- Test specimen: two wicker boards and a newspaper arranged in a vertical array.

<table>
<thead>
<tr>
<th></th>
<th>Flame spread</th>
<th>Mass loss</th>
<th>Visual observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2 = 15.9 \text{ vol}%$</td>
<td>NO</td>
<td>3.89 %</td>
<td>Only the bottom wicker board (the one directly hit by the pilot flame) ignited.</td>
</tr>
<tr>
<td>$O_2 = 20.9 \text{ vol}%$</td>
<td>YES</td>
<td>82.39 %</td>
<td>The fire spread almost immediately to all the three specimens.</td>
</tr>
</tbody>
</table>
Fire spread test - results

\[ \text{O}_2 = 15.9 \ \text{vol}\% \]

\[ \text{O}_2 = 20.9 \ \text{vol}\% \]
Test series - discussion

- Most test specimens did not ignite during the test performed at the lowest O₂ concentration (PP, paper).
  - Exception: wood crib (note: extremely severe heat source, alcohol).

- Difficult to ignite between 16.0 vol% and 17.0 vol% of O₂ concentration, flame and burning self-extinguished during PET, reduction in mass loss.

- No flame spread in the test performed at O₂ = 15.9 vol%.

- For the majority of the materials tested there is a sort of a response threshold in terms of burning between 17.0 vol% and 18.0 vol% of O₂ concentration.
Conclusions

• $14.5 \leq O_2 \leq 15.0 \text{ vol\%}$: hypoxic air limits ignition, prevents flame spread for all investigated materials.

• $16.0 \leq O_2 \leq 17.0 \text{ vol\%}$: hypoxic air does not fully prevent ignition but does lessen fire damages.

• Accurate assessment of materials, configuration and hazards to determine the correct $O_2$ concentration.

• More research to exploit and optimize further the potential of Hypoxic Air Technology.
Acknowledgments

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Thank you for your attention!