Paper 12: Numerical investigation of risks associated with decompression and atmospheric expansion of hydrogen

28 July 2022
Overview

- Background
- Hydrogen decompression tube test
- CFD model for atmospheric expansion of H\textsubscript{2} / CH\textsubscript{4}
- Simulation results
- Risk mitigation
- Conclusions
Background

- Application of renewable H₂ is an important part of CO₂ emission mitigation efforts.

- Transmission pipelines are the most appropriate long-term choice for H₂ distribution... If there is large and sustained demand.

- To facilitate the transport via pipelines, an accurate understanding of the decompression characteristics of H₂ is essential to control running ductile fracture.

- Limited experimental or numerical programs have been conducted with decompression of H₂ or NG+H₂ blends.
Future Fuels CRC engaged NOVA Chemicals to conduct a decompression tube test program.

The first test, conducted at TC Energy’s Gas Dynamics Test Facility in Didsbury, Alberta, Canada, investigated the decompression of pure H\textsubscript{2} from approx. 17 MPa.

The test indicated noise levels in excess of that witnessed at the site with NG and CO\textsubscript{2} mixtures. Ignition qualitatively witnessed ‘immediately’ after the onset of the rupture disc.

Possible reasons:
- Higher release velocity of H\textsubscript{2} (in the order of 1,000 m/s);
- Greater volumetric expansion (released volume over 2 times of that of NG).
Background

- Risks from overpressure wave, noise level, and ignition influence
  - The risk assessment of H\textsubscript{2} pipelines following an accidental release
  - The safety of controlled releases such as venting, blowdowns.

- A better understanding of the risks associated with high-pressure H\textsubscript{2} releases and their atmospheric expansion is warranted.

- Objective of this work:
  - Report the outcomes of the first pure H\textsubscript{2} decompression test;
  - CFD study to replicate the conditions of the decompression test on pure H\textsubscript{2};
  - Compare the risks from the decompression and expansion of pure CH\textsubscript{4} and H\textsubscript{2};
  - Discuss potential methods for risk mitigation.
Hydrogen decompression tube test
Hydrogen decompression tube test

Decompression tube at TCE
- 42 m long
- 38.1 mm internal diameter
- 14 pressure transducers (11 of which within the first spool)

First test
- Hydrogen (99.999% purity)
- Pressure: 16.62 MPa(a)
- Temperature: -1.5 °C

Schematic the decompression tube available at TCE

X-scored rupture disk
O-scored rupture disk
Hydrogen decompression tube test

Decompression wave speed

- Prediction using EPDECOM with GERG 2008 EOS
- Overall good agreement against measurements
- Minor difference at velocities above 600 m/s
- According to BTCM, the prediction produces a degree of non-conservatism
- Further work required to understand the role of friction and other factors
Hydrogen decompression tube test

Other experimental observations

- Level of noise considered louder than experienced from previous tests (NG, CO₂) at same initial P and T.

- Front window located behind the blocks experienced some damage; a situation which had not been witnessed in previous tests.

- The outflow of hydrogen constrained between the exit of the tube and the concrete blocks ignited “immediately” according to witnesses.

CFD simulations proposed to highlight the differences between H₂ and CH₄, and to explain the mechanisms supporting the experimental observations.
CFD model for atmospheric expansion of $\text{H}_2 / \text{CH}_4$
CFD model for atmospheric expansion of H$_2$ / CH$_4$

**CFD model**

- Replicates environment at TCE site
- Evaluate risks associated with H$_2$/CH$_4$ releases and atmospheric expansion:
  - Two-dimensional axisymmetric domain
  - Peng-Robinson EOS implemented for thermodynamics properties of H$_2$/Air or CH$_4$/Air mixtures
  - Realisable k-ε model for turbulence modelling
  - Density-based solver
  - Initial P: 17 MPa
  - Initial T: 0 °C
Simulation results
## Overpressure

### Overpressure histories predicted for $\text{H}_2$ at 17 MPa

<table>
<thead>
<tr>
<th>Overpressure (psi)</th>
<th>Expected damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>Typical pressure for glass failure.</td>
</tr>
<tr>
<td>0.40</td>
<td>Limited minor structural damage.</td>
</tr>
<tr>
<td>0.70</td>
<td>Minor damage to house structures.</td>
</tr>
<tr>
<td>1.0</td>
<td>Partial demolition of houses; made uninhabitable.</td>
</tr>
<tr>
<td>2.0</td>
<td>Partial collapse of walls and roofs of houses.</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>Non-reinforced concrete or cinder block walls shattered.</td>
</tr>
<tr>
<td>2.4-12.2</td>
<td>Range for 1-90% eardrum rupture among exposed populations.</td>
</tr>
<tr>
<td>3.0</td>
<td>Steel frame buildings distorted and pulled away from foundation.</td>
</tr>
<tr>
<td>5.0</td>
<td>Wooden utility poles snapped.</td>
</tr>
<tr>
<td>5.0-7.0</td>
<td>Nearly complete destruction of houses.</td>
</tr>
<tr>
<td>7.0</td>
<td>Loaded train cars overturned.</td>
</tr>
<tr>
<td>9.0</td>
<td>Loaded train box cars demolished.</td>
</tr>
<tr>
<td>10.0</td>
<td>Probable total building destruction.</td>
</tr>
</tbody>
</table>

**Damage expected at specific overpressure values**

- Overpressure of 0.15 psi is the typical pressure for glass failure.
- Overpressure of 0.40 psi results in limited minor structural damage.
- Overpressure of 0.70 psi causes minor damage to house structures.
- Overpressure of 1.0 psi leads to partial demolition of houses, making them uninhabitable.
- Overpressure between 2.0 and 3.0 psi causes partial collapse of walls and roofs of houses, as well as non-reinforced concrete or cinder block walls to shatter.
- Overpressure between 2.4 and 12.2 psi results in a range for 1-90% eardrum rupture among exposed populations.
- Overpressure of 3.0 psi results in steel frame buildings being distorted and pulled away from their foundation.
- Overpressure of 5.0 psi causes wooden utility poles to snap.
- Overpressure between 5.0 and 7.0 psi results in nearly complete destruction of houses.
- Overpressure of 7.0 psi results in loaded train cars overturning.
- Overpressure of 9.0 psi results in loaded train box cars being demolished.
- Overpressure of 10.0 psi results in probable total building destruction.

### Diagram

- 4.2 m downstream: Steel frame buildings distorted.
- 5.0 m downstream: Partial collapse of walls and roofs of houses.
- 10 m downstream: Partial demolition of houses, made uninhabitable.
- Overpressure histories with different labels indicating specific damage levels.

**Time (ms)**

- Overpressure (psig)**

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Simulation results:
Overpressure

Decay of maximum overpressure along the axis

Overpressure profile on the jet cross section at 4.2m (on the building wall at 10.7 ms)
Simulation results:

Overpressure

Overpressure histories: H₂ vs CH₄

Comparison between H₂ and CH₄ releases at 17 MPa:

- Shock wave produced by CH₄ travels slower than that produced by H₂
- CH₄ shock wave features initially a small peak
- Pressure wave produced by CH₄ is weaker than that produced by H₂
- Overpressures produced by CH₄ are half those produced by H₂

Steel frame buildings distorted
Partial collapse of walls and roofs
Partial demolition to house structures
Minor damage to house structures
Limited minor structural damage
Glass failure
Simulation results: Overpressure

Quantification of the blast energy using scaled distance concept:

- Equivalent blast energy of $H_2$ is five times that of $CH_4$
- The ratio of the equivalent blast energy to the product $u \cdot P$ (or A.u.P) is constant
- Equivalent blast energy scaled with the product of $u \cdot P$ (or A.u.P) can be used to estimate the relative values of the levels of overpressure for future tests involving various blends of NG+$H_2$

Calculation of equivalent blast energies:

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>4.2</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_2$</td>
<td>$NG$</td>
</tr>
<tr>
<td>Overpressure (psi)</td>
<td>4.7</td>
<td>2.46</td>
</tr>
<tr>
<td>Ambient Pressure (psi-a)</td>
<td>13.2</td>
<td>13.2</td>
</tr>
<tr>
<td>Normalized Overpressure</td>
<td>0.356</td>
<td>0.186</td>
</tr>
<tr>
<td>Scaled Distance*</td>
<td>5.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Equivalent Blast Energy, TNT (kg)</td>
<td>0.498</td>
<td>0.116</td>
</tr>
<tr>
<td>Exit Velocity, $u$ (m/s)</td>
<td>1083</td>
<td>228</td>
</tr>
<tr>
<td>Exit Pressure, $P$ (MPa-a)</td>
<td>4.199</td>
<td>4.647</td>
</tr>
<tr>
<td>Ratio of TNT/(u*P) x 1000</td>
<td>0.109</td>
<td>0.110</td>
</tr>
</tbody>
</table>
Simulation results:

Noise level

Noise levels with common noise sources and exposure time

<table>
<thead>
<tr>
<th>Noise level (dB)</th>
<th>Sound source</th>
<th>Exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>Front-end loader</td>
<td>8 hr</td>
</tr>
<tr>
<td>100</td>
<td>Sheet-metal workshop</td>
<td>15 min</td>
</tr>
<tr>
<td>120</td>
<td>Rock drill</td>
<td>8.8 s</td>
</tr>
<tr>
<td>130</td>
<td>Rivet hammer (pain can be felt)</td>
<td>0.9 s</td>
</tr>
<tr>
<td>140</td>
<td>Shotgun blast directly beside ear</td>
<td>0.09 s</td>
</tr>
<tr>
<td>150</td>
<td>Formula One car at full throttle</td>
<td>N/A</td>
</tr>
<tr>
<td>160</td>
<td>Inside jet engine</td>
<td>N/A</td>
</tr>
<tr>
<td>170</td>
<td>7,000-HP engine</td>
<td>N/A</td>
</tr>
<tr>
<td>180</td>
<td>1 pound of TNT detonating 4.5 m away (15 ft)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Sound pressure level histories predicted for H₂
Simulation results:

Noise level

Noise levels* produced by CH$_4$ expansion:

- Evolution of noise level with time is similar to that of the H$_2$ expansion
- The maximum noise level from the expansion of H$_2$ is higher by 3 to 17 dB relative to CH$_4$
- During the H$_2$ release compared to CH$_4$, there would be a perceived 25% increase in loudness at 5 m distance and about 50% increase in loudness at 10 and 15 m

* An increase of 3 dB in sound pressure level yields an increase in loudness of about 25%.
Simulation results:
Downstream temperature

Temperature contours near the jet exit: H₂

Temperature contours near the jet exit: CH₄
Simulation results:
Downstream temperature

Temperature evolution before 0.1 ms at where the highest temperature occurs
Risk mitigation
Risk mitigation

New cases simulated

Two cases simulated to evaluate the effect of concrete blocks for risk mitigation purpose:

- **Case 1** to account for the effect of shock wave bypassing the concrete block on the south side
- **Case 2** impedes the jet flow in all lateral directions
Risk mitigation: Combustion

- Concrete blocks are not able to prevent the development of the initial high temperature crown.
- Objects present in the H₂ stream can promote the chance of ignition.
- Prior work found that the overpressures due to a NG pipeline rupture are about twice those produced by the combustion of the gas.
  - Assuming ignition of H₂-O₂ produced an equivalent overpressure half that of the H₂ release, then temperature and overpressures associated to combustion may need to be considered in more details in the future.

H₂ concentration contours predicted in Case 2

- (a) 10 ms
- (b) 30 ms
- (c) 60 ms
Conclusions
Conclusions

- A shock tube test with pure H₂ was conducted at TCE Gas Dynamics Facility in Didsbury, Alberta, Canada.
  - Decompression wave speed successfully measured.
  - Good agreement between model and experiment observed.

- CFD models to better understand risks from overpressure wave, noise levels and ignition associated with H₂ decompression and expansion.

- Overpressure strength generated by H₂ release twice that of a CH₄ release.

- H₂ equivalent blast energy, expressed in kg of TNT, is about 5 times that of CH₄.
  - Without mitigations, damage may be caused to nearby building with both H₂ and CH₄ releases; the damage due to a H₂ release will be more severe.
Conclusions

- A decompression tube test with H\(_2\) is about 6 dB higher than a CH\(_4\) release, subjectively this is about 50% louder.

- High temperatures above the auto-ignition temperature are generated in a H\(_2\) release.
  - It is highly possible that auto-ignition would take place within the first instants of the release.

- As done with previous releases, risk mitigation is to place concrete blocks between the shock tube exit and the downstream facilities
  - The jet flow propagation should be impeded over a wider surface area, in both the downstream and lateral directions.

- Dedicated 3D simulations are being conducted
  - Purpose is to draw correlations between location downstream of different block configurations and test conditions (mixture, operating (P,T)).
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Co-authors and project participants

- **University of Wollongong, Australia**
  - Dr Xiong Liu
  - Prof Cheng Lu
  - Dr Guillaume Michal

- **NOVA Chemicals Corporation, Canada**
  - Dr Kamal K. Botros

- **TCE Gas Dynamics Facility, Canada**
  The shock tube facility is part of a high-pressure natural gas test facility located in Didsbury, Alberta, Canada and is owned by TC Energy. Permission to use the shock tube and associated auxiliary system, unique instrumentation features and accurate data acquisition and processing schemes are greatly appreciated.
Thank you