Snapshots of liquid hydrogen safety research and possible knowledge gaps

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The Context

http://www.jobs.net/jobs/usairliquide/en-us/

RR987 - Ignited releases of liquid hydrogen – HSE (2014)


http://www.warwick.ac.uk/warwickfire
The Context

Liquid hydrogen property

- LH2 POOL: [http://h2bestpractices.org/h2introduction/basics/liquid_behaviors.asp](http://h2bestpractices.org/h2introduction/basics/liquid_behaviors.asp)

The volume ratio of liquid to gas is 1:848)

Comparing with LNG: 1:600

Temperature: -162 °C
The associated hazards

- Air Products Safetygram 9: Liquid hydrogen
- EIGA (European Industrial Gas Association): SAFETY IN STORAGE, HANDLING AND DISTRIBUTION OF LIQUID HYDROGEN
- *Air Liquide* Gas Encyclopedia

- Hazards of liquid hydrogen: Position paper RR769 – HSE
The associated hazards

RR987 - Ignited releases of liquid hydrogen – HSE (2014)

- Jet & potential ignition
- Liquid hydrogen pool fire
- Jet fire
- Secondary explosion

More to be identified in the last two slides
Outline

• **Pool spreading**
  − Dataset available for model validation – pool spreading
  − Earlier work of Verfondern and co-workers (1994 to 2007…)
  − Some recent work of others

• **Jet fires, pool fires and secondary explosion**
  − Some more recent experimental and modelling investigations

• **Possible knowledge gaps**
Dataset available for model validation – pool spreading

• BAM (Marinescu-Pasoi and Sturm, 1994)

• NASA (Chirivella and Witcofski, 1986) trials

• HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)
HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)

Figure 21 Liquid hydrogen during the release

Figure 23 Hydrogen concentrations at varying distances from the release at a fixed height of 0.25 m

TEST 6 – VERTICALLY DOWNWARD RELEASE 100 mm ABOVE THE GROUND
M. Ichard, O.R. Hansen, P. Middha, D. Willoughby,
CFD computations of liquid hydrogen releases

• FLACS with HEM, rain out and pool model, condensation of oxygen and nitrogen

• Knowledge gaps identified:
  – Source term evaluation
  – better representation of the turbulence
  – accurate model to evaluate source terms for flashing releases is needed.
Pool spreading modelling

- **Integral models**
  - GASP (Webber, 1990)

- **Shallow layer models**
  - Verfondern and co-workers (1994 to 2007…)

- **CFD models**
  - ADREA-HF (Statharas et al., 2000), FLACS (FLACS, 2010), FLUENT and CFX (Schmidt et al., 1999, Molkov et al., 2005, Sklavounos and Rigas, 2005).
Verfondern and co-workers (1994 to 2007...)

- Simulation of accidental spills of cryogenic hydrogen in a residential area
  *Cryogenics, Volume 34, Supplement 1, 1994, Pages 401-404*
  U. Schmidtcjen, L. Marinescu-Pasioi, K. Verfondern, V. Nickel, B. Sturm, B. Dienhart

- Experimental and theoretical investigation of liquid hydrogen pool spreading and vaporization
  K. Verfondern, B. Dienhart

- Pool spreading and vaporization of liquid hydrogen
  K. Verfondern, B. Dienhart

- 3D Modeling of the Different Boiling Regimes During Spill and Spreading of Liquid Hydrogen
  *Energy Procedia, Volume 29, 2012, Pages 244-253*
  C. Jaekel, K. Verfondern, S. Kelm, W. Jahn, H.-J. Allelein

- Validation strategy for CFD models describing safety-relevant scenarios including LH2/GH2 release and the use of passive auto-catalytic recombiners
  Christian Jäkel, Stephan Kelm, Ernst-Arndt Reinecke, Karl Verfondern, Hans-Josef Allelein

http://www.warwick.ac.uk/warwickfire
LAUV code: Verfondern and co-workers (1994 to 2007...)

Fig. 5. Comparison of LN2 pool measurements with respective LAUV calculations instantaneous release of 40 l (top) and continuous release at a varying rate over 121 s (bottom).
HSL data (RR986 - Releases of unignited liquid hydrogen – HSE, 2014)

Fig. 2 – Picture of the hydrogen jet for Test-07 (170 s after start of release).

Figure 11. Solid deposit 3 minutes after release

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Boiling temperature Celsius</th>
<th>Boiling temperature Fahrenheit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>-183°</td>
<td>-297°</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>-196°</td>
<td>-320°</td>
</tr>
<tr>
<td>Neon</td>
<td>-246°</td>
<td>-411°</td>
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<tr>
<td>Hydrogen</td>
<td>-253°</td>
<td>-423°</td>
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<tr>
<td>Helium</td>
<td>-270°</td>
<td>-452°</td>
</tr>
</tbody>
</table>
CFD computations of liquid hydrogen releases
M. Ichard, O.R. Hansen, P. Middha, D. Willoughby

Fig. 4 – [Left] Minimum temperature as a function of distance at steady state conditions for the horizontal release Test 07 0.75 m above the ground. [Right] Temperature time-series for Test-07 at sensor M26: $X = 7.5 \text{ m}; Z = 0.75 \text{ m}$. 
RR987 - Ignited releases of liquid hydrogen – HSE (2014)

Ignition downstream from the release point
Test 6
- Initial deflagration burn back
- Flame front reached 50 m/s
- Uplift of the flame front
- Secondary explosion occurred emanating from the liquid/solid pool location
- Jet flame (wind speed 1.9 m/s)
RR987 - Ignited releases of liquid hydrogen – HSE (2014)

Figure 4.2: Radiometer readings from ignited release (Test 4)

Figure 4.4: Radiometer readings from ignited release (Test 6) exhibiting a secondary explosion
RR987 - Ignited releases of liquid hydrogen – HSE (2014)

Figure 4.5: Ignition of the vapour cloud during Test 10 during low wind conditions.
Possible knowledge gaps (1)

Tests in in controlled laboratory conditions

- Source term quantification
- Solid deposition, especially oxygen
- Secondary explosion

Theoretical and modelling

- Coupled shallow layer and CFD, i.e. spill, cloud formation and dispersion
- Insight and predictive tools for the ignited release

Scenarios

- The future hydrogen station will be co-hosted by gasoline stations. The associated risks need to be built into future safety research.
Possible knowledge gaps (2)

Possible DDT

- Large quantities in open but congested area
- Potential for DDT
- Needs theoretical understanding or very large scale experiments

(g) 3639 ms: secondary explosion

- The lack of available models that can be applied to LH2 releases.

- Lack of experimental data on LH2 pool fires and none at large scale.

- Some small scale experiments were conducted in a Dewar so the observed mass burning rate was probably much lower than would be expected during the early stages of a fire on a normal substrate.

- No experimental data on BLEVEs (Boiling Liquid Expanding Vapour Explosion or fireball) was identified; although such an incident has occurred demonstrating it is a possible hazard.

- The lack of quantitative data on failure frequency and ignition probability (?)