Hydrogen behaviour when released in confined atmospheres: experimental study and numerical simulations

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Outline

- Introduction – Motivations
- Focus of project
- Methodology
- Literature review:
  - Experiments
  - CFD simulations
- Planned experimental and simulation work
- Guidelines
- Conclusions and acknowledgements
Use of hydrogen systems in confined environments

- garage
- Electrolyser
- Underground storage (refuelling station)
H₂ leaks for confined systems – scenarios 1/2

- Catastrophic release in confined spaces:
  - hazardous explosive atmosphere to be feared,
  - conventional mitigation systems (ventilation) inappropriate,
  - Safety is handled by the system design itself (early detection and emergency shut-off, PRD routed outside...)
H2 leaks for confined systems – scenarios 2/2

- Accidental (pipe crack, gasket failure,...) / chronic (permeation) confined leaks,
  - more likely than catastrophic release,
  - some release rate are not detectable by integrated safety sensors,
  - such leaks can be handled by external safety systems (ventilation, emergency inverting, hydrogen removal systems,...)

→ Do hazardous explosive atmospheres (ATEX) form systematically?
→ Where would they preferably form?
→ What would be the best design for safety barriers (performance, optimisation)?
Project focus

- Concentrate on accidental releases (below 1g/s) rather than catastrophic releases.
- Explosive atmosphere (ATEX) will form systematically at release point. However, ATEX volume will be moderate for most release rate considered.

Focus on H2 dispersion in confined atmosphere:
- How hydrogen will disperse inside the closed volume depending on the flow regime (jets, plume, ...)?
- What is the effect of leak impingement and leak direction?
- Is hydrogen accumulating below the ceiling a relevant forecast for any leak?
- How quickly can an ATEX be formed?
- Effect of vent positioning on hydrogen removal?
- Where would hydrogen detectors be best located?
- Are existing guidelines appropriate?
Project methodology and output

- Perform literature review (past experiments and modelling + existing guidelines on the safe use of H₂ systems),
- Perform new experiments to fill gaps,
- Perform CFD modelling (pre-calculation of tests, benchmarks for code validation),
- Results consolidation in a guidance report.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Released substance</th>
<th>Year</th>
<th>Volumetric flow rate (lt/s)</th>
<th>H2 mass flow rate (g/s)</th>
<th>Exit velocity (m/s)</th>
<th>Enclosure volume (m3)</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swain garage</td>
<td>He</td>
<td>1998</td>
<td>2.00</td>
<td>0.170</td>
<td>0.10</td>
<td>66.83</td>
<td>How should existing garages be modified to make them suitable for hydrogen fueled vehicle storage.</td>
</tr>
<tr>
<td>GEOMET tests</td>
<td>H2</td>
<td>1993</td>
<td>0.28</td>
<td>0.024</td>
<td></td>
<td>45.50</td>
<td>Gather data that could be used to determine the necessary vent size to keep hydrogen concentrations below 2% in a residential garage, during the charging cycle of an electric vehicle.</td>
</tr>
<tr>
<td>Swain hallway</td>
<td>H2</td>
<td>1999</td>
<td>0.94</td>
<td>0.080</td>
<td>0.02</td>
<td>2.62</td>
<td>CFD Validation</td>
</tr>
<tr>
<td>JARI box</td>
<td>H2</td>
<td>2004</td>
<td>0.17</td>
<td>0.014</td>
<td>0.10</td>
<td>1.00</td>
<td>Examine the diffusion behaviour of hydrogen in an enclosed space with various release speed.</td>
</tr>
<tr>
<td>JARI box</td>
<td>H2</td>
<td>2004</td>
<td>0.17</td>
<td>0.014</td>
<td>0.20</td>
<td>1.00</td>
<td>Idem</td>
</tr>
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<td>JARI box</td>
<td>H2</td>
<td>2004</td>
<td>0.17</td>
<td>0.014</td>
<td>3.40</td>
<td>1.00</td>
<td>Idem</td>
</tr>
<tr>
<td>CEA-MH1</td>
<td>He</td>
<td>2004</td>
<td>5.88</td>
<td>0.500</td>
<td>1.33</td>
<td>100.00</td>
<td>Gather data for CFD validation</td>
</tr>
<tr>
<td>BMW test</td>
<td>H2</td>
<td>2004</td>
<td>0.187</td>
<td>0.017</td>
<td>Boil off</td>
<td>36.2</td>
<td>Validate that no hazardous ATEX could from with minimum ventilation</td>
</tr>
<tr>
<td>BMW test</td>
<td>H2</td>
<td>2004</td>
<td>0.0935</td>
<td>0.0085</td>
<td>Boil off</td>
<td>36.2</td>
<td>Idem</td>
</tr>
</tbody>
</table>
Literature review: Swain experiments

Release speed: **0.02m/s**
Release flow rate: **0.08g/s**
Release diameter: **240mm**
Release duration: **1200s**

Release speed: **0.1m/s**
Release flow rate: **0.17g/s**
Release diameter: **160mm**
Release duration: **7200s**
Literature review: CEA MISTRA experiments

Release speed: **1.3m/s**
Release flow rate: **1g/s** (He)
release diameter: **75mm**
Release duration: **1800s**
Literature review - CFD capabilities and needs

NCSRD simulation of Swain experiments (ADREA code)

CEA simulations (CAST3M code)

FZK simulations (GASFLOW code)
Literature review - CFD capabilities and needs

Open benchmark performed in HYSAFE: H2 injection followed by “diffusion” phase lasting 250 min. Predict cloud formation & mixing (from E. Gallego et al., ICHS, 2005)

Scatter
Most codes underpredict H2 concentration at bottom of vessel

Also experimental data lacking
Conclusions from literature review 1/2

- Most experimental data related to garage safety
- Poor instrumentation generally used (4 sensors...),
- Issue of data confidentiality or accessibility
- Mainly used to validate safety concept and not to improve understanding of hydrogen dispersion and diffusion,
- Range of flow rate investigated are in line with what we consider as non-catastrophic release,

→ Some experimental data still needed
→ CFD deficiencies observed → validation needed
Conclusions from literature review 2/2

- Open questions on dispersion mechanisms: Provide phenomenological answers (detailed experimental data & improved CFD modelling), investigate release momentum effect, ...
- Open questions on explosive atmosphere formation (size, delay): Provide answers for risk assessment ($V_{ATEX} = f(\text{release geometry, speed, ventilation})$),
- Test hydrogen detection techniques in real conditions
- Need to gain more practical experience for contribution to guidelines
New experimental work: development/application of new instrumentation techniques

- Ultrasound detectors
- NH3Cl seeding + visualisation + opacimetry
- Mass spectrometry
- Mini-catheterometers (thermal-conductivity sensors)
New experiments at INERIS: Gallery (2005)

H=2.9 m
W=3.8 m
L=7.2 m
V= 78 m³

- Use of Hydrogen,
- Instrumentation: ammonium chlorine seeding + argon laser visualisation + opacimetry + catharometers,
- Output raw results: film of hydrogen release and dispersion, H₂ concentration versus time at 12 different locations.

Slide 16
New experiments at CEA: Garage (2006-08)

- Dense instrumentation
- Use of LDV, PIV
### Test matrix

<table>
<thead>
<tr>
<th>Phenomena which affect H₂ dispersion and ATEX formation</th>
<th>Gallery (H₂)</th>
<th>Garage (He &amp; H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of release direction</td>
<td></td>
<td>Upward, downward, horizontal</td>
</tr>
<tr>
<td>Effect of release speed</td>
<td>Release speed from 0.2 to 1000 m/s</td>
<td></td>
</tr>
<tr>
<td>Effect of impingement</td>
<td></td>
<td>Under plate releases</td>
</tr>
<tr>
<td>Effect of forced and natural ventilation</td>
<td>0 &amp; 3 air change per hour</td>
<td>Various natural and forced ventilation</td>
</tr>
<tr>
<td>Effect of laminar diffusion</td>
<td>Hydrogen concentration measured once release has stopped</td>
<td>Hydrogen concentration measured once release has stopped</td>
</tr>
<tr>
<td>Effect of turbulence (natural convection,...)</td>
<td></td>
<td>Turbulence monitored</td>
</tr>
</tbody>
</table>
CFD Programme (1/2)

- Pre-test calculation undertaken (NCSR, Gexcon, HSL, UU, CEA,...) to support sensor location, to choose most interesting experimental cases as well as to debug future CFD benchmark,

- Tests from each campaign chosen for blind CFD benchmark exercise (HySafe). Open to external participants.
CFD Programme (2/2)

- Expected output results: evolution of ATEX volume and mass versus time (can not be measured directly), H2 concentration versus time at each sensor location,... + description of the
- applied modeling methodology
  - Recommended models and best practices guidelines.
  - Use of CFD to predict ATEX volume and location.

<table>
<thead>
<tr>
<th>Participation organisation</th>
<th>Used tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEA</td>
<td>CAST3M</td>
</tr>
<tr>
<td>DNV</td>
<td>tbd</td>
</tr>
<tr>
<td>FZJ</td>
<td>tbd</td>
</tr>
<tr>
<td>HSL</td>
<td>tbd</td>
</tr>
<tr>
<td>FZK</td>
<td>GASFLOW</td>
</tr>
<tr>
<td>Gexcon</td>
<td>FLACS</td>
</tr>
<tr>
<td>INERIS</td>
<td>PHOENICS</td>
</tr>
<tr>
<td>NCSRd</td>
<td>ADREA</td>
</tr>
<tr>
<td>UU</td>
<td>FLUENT</td>
</tr>
<tr>
<td>UPM</td>
<td>CFX</td>
</tr>
</tbody>
</table>
• Can we use existing examples from other gases?
• We need recommendations to be harmonised & based on practical data.
Achievements so far…

- Review and study of available data,
- Development and use of innovative and extended instrumentation to further investigate accidental phenomena,
- Elaboration of a comprehensive and complementary experimental programme to cover 2005-2007 period,
- Initiation of a comprehensive CFD benchmarking effort,
- Critical review of existing guidelines for the safe use of systems in confined spaces.
Acknowledgements - Collaborations

- Part of this work performed in the framework of the HYSAFE Network of Excellence (2004-09)
- Also in the framework of future DRIVE project (French Research Programme PAN-H) (2006-08)
- Part of the project results to be included in IEA Task 19 Hydrogen Safety (2005-08)