Hydrogen Safety for Marine Applications

FLACS Users Group meeting
Steinsland 22-23 May 2018
Olav Roald Hansen – Lloyds Register - Risk Management Consulting, Bergen, Norway

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Lloyd’s Register - introduction

LR RMC (HQ Norway) part of LR Energy
- Main activity risk assessments for O&G installations
- Hydrogen risk and consequence studies increasing
LR Marine (Southampton)
- Ship classification, including IGF alternative design
- LR RMC contributes as subject matter experts

LR RMC hydrogen safety assessments
- Various H₂ refuelling stations
- H₂ production units
- Fast passenger ferry projects
- Car ferry project
- R&D project MoZEES
- And more …

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Motivation

Hydrogen very different from conventional marine fuels, including LNG, MUCH…

- … higher reactivity (6x burning velocity)
- … wider flammability (4-75% vs 5-15%)
- … higher ignition probability (MIE ~15-20x lower)

Safe design more challenging, strong buoyancy and low reactivity & energy < 15% to be exploited

LH2 more practical for large scale marine implementation than compressed gas

- Transport more efficient
- Bunkering is faster
- Energy density better
- Storage likely more robust in external fires

Several marine projects seem to consider LH2

- Quite a few of these seem not to acknowledge LH2-vapour may be dense
- Will influence optimal tank location and hazard distances

SF Breeze report: Generally good work and interesting reading. Wording about LH2-vapour buoyancy confuses

Olav Roald Hansen - relevant background

25 years CFD-dispersion/explosion modelling FLACS

- Testing, development, global sale and support
- 2004-2010 EU-project HySAFE (25 partners in Europe)
- 2004-2012 IEA HIA Task 19/31 Expert Group H2 Safety
- Various consulting work H2 safety
- 15+ scientific articles H2 safety, 50+ within explosions/dispersion/risk

LNG consequence modelling

- Led development and validation of LNG pool spread models
- NFPA Model Evaluation Protocol - validation study
- FLACS accepted by PHMSA for NFPA-59A as only CFD tool 2011

Flashing releases

- EU project FLIE – study of butane/propane releases
- US DHS TiCs expert group – chlorine/ammonia releases
LR risk assessment approach

Screening assessment using xls-sheet formulas
- Segment inventory and outflow (real gas)
- Dispersion distances and cloud volumes
- Jet fire radiation distances
- Pressurized vessel burst - projectiles
- TNO multi-energy explosion loads
- Ignition probability

Computational Fluid Dynamics (CFD) when required
- Liquid hydrogen LH2
- H2-gas scenarios where geometry matters
  - Impingement/congestion/confinement > 15% H2
  - Indoor scenarios / accumulation > 15% H2
- Explosions – deflagrations, DDT and vessel burst
  - If detailed explosion load pattern is required

MoZEES – Norwegian Research Center for Zero Emission Transport

- Established in 2017
- 260 MNOK, 8 years and 19 PhD and postdocs

Battery and hydrogen – technology value chains

Presented by F. Aarskog and O. R. Hansen at H2FC Conference in Trondheim May 15, 2018
H2 Maritime Case Study – Research Team

- Øystein Ulleberg, IFE
- Fredrik Aarskog, IFE
- Frederico Zenith, SINTEF
- Sepideh Jafarzadeh, NTNU
- Trond Strømgren, Maritime Association Sogn & Fjordane
- Olav Roald Hansen, Lloyd’s Register

Selection of case:
GKP7H2 – Pre-Project (Green Coastal Shipping Program)

- Length: 30 meters
- Installed motor power: 2 × 600 kW
- Speed: 28 knots (52 km/hour)
- Passenger capacity: 100 persons
- Reference route:
  - Florø-Måløy, 1 trip per day: 68.4 nm
  - Nordre rute, 2 trips per day: 45.0 nm
  - Total 113.4 nm (210 km) per day (on weekdays)
- Estimated max. daily hydrogen consumption: ca. 380 kg
- H2-storage: 3 × 150 kg @ 250 bar

Source: https://www.dnvgl.no/maritime/grønt-kystfartsprogram/rapporter.html
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H2 Maritime Case Study – Scope of Work

- Duty cycle of this ship in normal route (NTNU, IFE)
  - GKPH2 pre-project: Estimation of fuel consumption
  - Measurements/data logging by Brødrene Aa

- Fuel cell energy system design (IFE, SINTEF)
  - Battery and FC capacities (kWh, kW) and dimensions (kg, m³)
  - Hydrogen storage capacity (kg H₂) and dimensions (kg, m³)

- Economic evaluation (SINTEF, IFE)
  - OPEX/CAPEX; limit study to this exact ship on this exact route
  - Economic parameters (FC: $/kW, tanks: $/kWh, etc.)

- Safety & Risk analysis (LR, IFE)
  - Pre-HAZID on simplified P&ID
  - Risk analysis on preliminary mechanical design (with safety zones)

- H2-bunkering not part of the study

Preliminary Hazardous Areas and Safety Zones

A more detailed assessment per IEC60079-10-1 should conclude that hazardous zone should only extend upwards from vent mast (due to buoyancy), will be influenced by solid fences, and no zone should be necessary inside high pressure storage tanks.
Hydrogen Risk Assessment Approaches

Most of study performed using xls-sheet models

CFD only applied for a couple of scenarios
Concept Risk Assessment – IGF Requirements

Requirements; IGF – equivalent safety to conventionally fuelled vessel (diesel)

**Challenge 1:**
- What is equivalent safety level? To what? How to demonstrate?
  - TOI (2001) – 0.6 dead per 1E9 passenger km 1970-1994
  - NMA (2002) – new technology 1.0 dead per 1E9 km OK
    - < 0.5-1.0 fatalities per 1E9 km from H2 systems likely OK
  - Vessel may spend significant time in harbour
    - Decided to evaluate against DSB land planning regulations (not required, but may support case)

**Challenge 2:**
- Early stage, many design details unclear
  - Need to take numerous assumptions
  E.g. general best practice to minimize pipe diameters, limit jet flame risk, ensure leaks vented upwards etc.

Presented by F.Aarskog and O.R.Hansen at H2FC Conference in Trondheim May 15, 2018

Risk Assessment Approach

Systems generally sorted and evaluated by pressures and volumes, typical choice will be

<table>
<thead>
<tr>
<th>Hydrogen systems</th>
<th>Hazard</th>
<th>Fatality potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage tanks</td>
<td>vessel burst (w/wo ignition)</td>
<td>significant</td>
</tr>
<tr>
<td>HP piping/equipment</td>
<td>leak, jet fire, explosion</td>
<td>limited</td>
</tr>
<tr>
<td>LP piping/equipment</td>
<td>leak, jet fire, explosion</td>
<td>marginal</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>leak and explosion</td>
<td>marginal</td>
</tr>
<tr>
<td>Emergency vent</td>
<td>radiation/explosion</td>
<td>must be designed safe</td>
</tr>
</tbody>
</table>

Good design may limit consequences from most scenarios

Catastrophic tank rupture may be exception, expected frequency 1E-6 to 1E-7/y (?)
  - Very high pressures (of short duration) – should consider measures to limit likelihood and mitigate

Presented by F.Aarskog and O.R.Hansen at H2FC Conference in Trondheim May 15, 2018

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Concept Risk Assessment – Conclusions

**Estimated of passenger risk:**
- For all identified scenarios fatality distances and frequencies were estimated
- Fatality risk to passengers and crew was estimated and compared against 0.5-1.0 per 1E9 passenger km

**DSB consultation distances (hensynssoner) if fixed installation**
- Inner zone: ??m
- Middle zone: ??m (no shops or homes allowed)
- Outer zone: ??m (no hotels, schools, shopping malls)
- Based on this it was concluded whether there should be any concerns mooring the vessel in a busy harbour

*Preliminary assessment indicates that the fatality risk will not be significantly higher than for a conventionally fueled vessel*

Estimates were approximate and depend on
- Provided preliminary information available
- LR assumptions on pipe dimensions and mitigation methods

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Relevant studies for LH2 risk assessments

**Bunkering studies – ISO 20519 (LNG) is relevant standard (ref. DSB)**
- Safety Zone and Monitoring & Security Zone (ISO 20519)
- Inner, middle and outer consultation zones – DSB/Seveso
- Hazardous zone – IEC60079-10-1

Credible releases LFL or QRA-inner zone can be used to define Safety Zone

**Risk related to tanks and TCS (confined & semi-confined spaces)**
- Acceptable risk to be demonstrated (ref. IGF alternative design)
  => Risk “equivalent to conventionally fuelled vessel”

**Gas mast evaluations**
- Ensure safe venting of LH2 and compressed H2

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LH2 releases – buoyant or dense?

- LH2 pool releases (NASA, BAM, HSL)
  
  Pool releases ~10 kg/s

  Thus, is the conclusion that an LH2 spill will have positive buoyancy?


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  Pool releases ~10 kg/s

  Thus, is the conclusion that an LH2 spill will have positive buoyancy?

LH2 releases – buoyant or dense? – Frequently misunderstood

Relative density for selected fuels (air at 20°C ~ 1)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Molecular weight</th>
<th>Boiling point</th>
<th>Density room temperature</th>
<th>Density BP – pool spill (heat from ground)</th>
<th>Density sprays (heat from ambient air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>16</td>
<td>-161°C</td>
<td>0.55</td>
<td>1.5</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Ammonia</td>
<td>17</td>
<td>-33°C</td>
<td>0.59</td>
<td>0.73</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2</td>
<td>-253°C #</td>
<td>0.07</td>
<td>1.01</td>
<td>&gt;&gt; 1</td>
</tr>
</tbody>
</table>

* LH2 releases also lead to N2 and O2 condensation/freezing

- LH2 pool releases – heat from ground (LH2 tests by NASA, BAM, HSL) => neutral/weakly buoyant
- LH2 spray releases – heat from surrounding air (LH2 experiments KIT, HSL) => dense
- LH2 much less likely to form pool than LNG

Bunkering LNG vs LH2: Credible release ISO 20519 – 10 bar ¼” (6.35 mm) instrument connection

<table>
<thead>
<tr>
<th>Property</th>
<th>LH2</th>
<th>LNG</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid density</td>
<td>70 kg/m³</td>
<td>422 kg/m³</td>
<td>1 : 6</td>
</tr>
<tr>
<td>Outflow velocity</td>
<td>168 m/s</td>
<td>69 m/s</td>
<td>2.5 : 1</td>
</tr>
<tr>
<td>Leak rate (Cd=0.62)</td>
<td>234 g/s</td>
<td>768 g/s</td>
<td>1 : 3.3</td>
</tr>
<tr>
<td>Combustion heat</td>
<td>33.2 MJ/s</td>
<td>42.6 MJ/s</td>
<td>1 : 1.3</td>
</tr>
<tr>
<td>Stoichiometric</td>
<td>29.5%</td>
<td>9.5%</td>
<td>3 : 1</td>
</tr>
<tr>
<td>LFL</td>
<td>4%</td>
<td>5%</td>
<td>1 : 1.25</td>
</tr>
<tr>
<td>Energy density LFL</td>
<td>0.51 MJ/m³</td>
<td>2.0 MJ/m³</td>
<td>1 : 4.0</td>
</tr>
</tbody>
</table>

Comparable distances to ~half of stoichiometry Methane 5% (=LFL) & Hydrogen 15%
Distance to LFL for Hydrogen (4%) much larger

Video release Down and Horizontal
Bunkering LNG vs LH2: Credible release ISO 20519 – 10 bar ¼” (6.35 mm) instrument connection

ISO 20519 conclusions LH2
- Challenging to define Safety Zone by credible release
- QRA required (leak and wind freq., ignition prob., explosion, fire)
- Minimize possible leak sizes, optimize safety systems, shield unwanted leak directions, ++

<table>
<thead>
<tr>
<th>Results</th>
<th>LH2</th>
<th>LNG</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFL distance</td>
<td>83 m</td>
<td>16 m</td>
<td>5 : 1</td>
</tr>
<tr>
<td>Flammable cloud</td>
<td>630 m³</td>
<td>15 m³</td>
<td>42 : 1</td>
</tr>
<tr>
<td>Explosive cloud (Q9)</td>
<td>15 m³</td>
<td>4 m³</td>
<td>3.8 : 1</td>
</tr>
</tbody>
</table>

Gas Mast Evaluations

LH2 released through vent mast
- Will initially evaporate due to heat transfer from gas mast (gas release from mast)
- When gas mast is cooled LH2 may reach exit (LH2-release from mast)

If released in gas phase
  - No flammable gas to be expected below exit

If released as LH2
  - Hydrogen-air mixture will be dense and fall

Depending on gas mast height and wind flammable gas may fall to deck

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Summary and conclusions

Several marine hydrogen projects in Norway and elsewhere being considered
Hydrogen properties very different from conventional fuels, safe design more challenging

LH2 is in many ways more practical to handle than compressed gas hydrogen

LH2 will most likely show dense gas behaviour if released during bunkering or piping
- LH2 safety distances (to LFL) are much larger than for LNG
- Design/layout should reflect potential hazards from dense LH2-releases
- Possibility for oxygen/nitrogen snow – oxygen doped air
- If gas mast is sufficiently cooled dense LH2-vapour may fall to vessel

The dense gas behaviour makes a safe design even more challenging. For equivalent risk level to conventional fuels (IGF requirement) safety should be focus from the beginning
- Optimize design/layout and mitigation
- Direct «copy-paste» of LNG-design not recommended

Questions?

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