SIMULATION OF HYDROGEN MIXING AND PAR OPERATION DURING ACCIDENTAL RELEASE IN A LH₂ CARRIER ENGINE ROOM

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OUTLINE

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- Results
  - Unmitigated Scenario
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INTRODUCTION

Next-generation LH2 carriers may use the boil-off gas from the cargo tanks as additional fuel for the engine.

Safety considerations were made for the potential failure of the feed lines and release of GH2 into the room of the propulsion system.

The worst-case scenario assumes a power blackout (failure of active ventilation systems) and an undetected leak.

Hydrogen may accumulate locally and form a flammable mixture with air.

To prevent endangering the crew and the ship, the installation of passive auto-catalytic recombiners (PARs), was investigated in a collaboration between Forschungszentrum Jülich and Kawasaki Heavy Industries.
INTRODUCTION

Passive Auto-Catalytic Recombiners

- PARs are qualified as safety systems under the conditions of nuclear power plant accidents and enable flameless conversion of Hydrogen to steam.
- Due to the exothermal reaction, a buoyancy-driven flow is induced through the chimney on top of the catalyst section.
- It inherently feeds the surrounding hydrogen/air mixture into the PAR.
- Being an entirely passive safety measure, PARs will operate even in case of blackout and without crew interaction.
The geometry is based on an existing LNG carrier

- The engine room is located in the rear part of the hydrogen carrier.
- The two main boilers are connected by each three pipes to the gas hood at the rear side of the engine room.
- The pipes are housed in a rectangular, non-pressure-resistant protection tube.
The geometry is based on an existing LNG carrier

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- The two main boilers are connected by each three pipes to the gas hood at the rear side of the engine room.
- The pipes are housed in a rectangular, non-pressure-resistant protection tube.
- The room of the propulsion system is connected to the environment by the ventilation ducts.
- The simplified geometry resolves the large components as well as the open cross-sections in the ceilings, but not the small structures (piping, valves, walking grids etc.).
MODELLING APPROACH

PAR System

- 10 optimal PAR positions determined with 'unmitigated reference case'
  - In flow path of H2 plume (pos 1&2) opening in ceiling of upper deck.
  - Back wall of A-C decks, where H2 accumulations were observed (pos 3-10).
  - Base concept (PAR-1).
  - Parametric study to assess impact of PAR size:

<table>
<thead>
<tr>
<th>Recombiner system</th>
<th>PAR type at positions 1 and 2</th>
<th>PAR type at positions 3 to 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR-1</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>PAR-2</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>PAR-3</td>
<td>Large</td>
<td>Small</td>
</tr>
</tbody>
</table>

(capacity of a large PAR ~ 5x of a small one)
MODELLING APPROACH

Numerical Grid

- Multi-block structured mesh, generated with ANSYS ICEM CFD
- 2x refined mesh resolution above 2\textsuperscript{nd} deck.

<table>
<thead>
<tr>
<th>Mesh statistics</th>
<th>without recombiners</th>
<th>with recombiners</th>
</tr>
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<tbody>
<tr>
<td>Total number of fluid elements</td>
<td>~ 1,600,000</td>
<td>~ 2,800,000</td>
</tr>
<tr>
<td>Volume size of an average volume (m(^3))</td>
<td>~ 0.013</td>
<td>~ 0.008</td>
</tr>
<tr>
<td>Edge length of an average volume (m)</td>
<td>~ 0.24</td>
<td>~ 0.20</td>
</tr>
</tbody>
</table>

Grid Quality Metrics

- Aspect ratio: < 9
- Cell volume ratio / growth rate: < 6.0
- Minimum face angle (\(^\circ\)): > 27
MODELLING APPROACH

Hydrogen Mixing and Transport Processes

- Baseline model for hydrogen mixing and mitigation
  (comprehensively validated for nuclear reactor containment atmosphere mixing)
  - ANSYS CFX 14
  - URANS (k-\(\omega\) SST model incl. full buoyancy effects)
  - Ideal gas equation of state
  - REKODIREKT PAR model
  - 2\textsuperscript{nd} order discretization in time and space
  - Adaptive time stepping (ave. CFL \(\sim 1\), \(\Delta t \sim 0.3\)s)

- Initial and boundary conditions:
  - Air @ 30\(^\circ\)C and 50% rel. humidity
  - Free circulation through ventilation ducts (\(\zeta=21.5\))
  - Thermal buoyancy from hot engine / colder walls
  - \(\text{H}_2\) release rates 0.445 - 5 g/s
RESULTS

Unmitigated Scenario

- The released hydrogen instantly forms a buoyant plume, which breaks up when passing through the ceilings.
- A natural circulation is formed as light H$_2$-rich gas is leaving the engine room through the upper vents and air (< 1 m$^3$/s) enters at the lower vents (D-deck).
- Hydrogen disperses almost homogeneously throughout the upper decks above the injection elevation with concentration of < 1 vol.%.
- Considerable part of the released hydrogen is removed by the natural circulation.

➢ Major source of uncertainty due to unresolved internal structures (piping, walking grids, small components etc.) and entrainment boundary condition.
RESULTS

Unmitigated Scenario

- Formation of a hydrogen-rich cloud depends on the release rate
  - No considerable flammable gas cloud (LFL 4 vol.%.) for release rates of 0.5 and 1 g/s.
  - Flammable clouds of ~8 m³ (2 g/s) and ~30 m³ (4 g/s) within the first 90 min primarily within ceiling layer above break location.
  - Hydrogen accumulation at the rear side of the engine room where flow is stagnating.

- PAR placed along flow path and positions with increased H₂ concentrations.
RESULTS

Mitigated Scenario

- The recombiners:
  - reduce H\textsubscript{2} concentration in the rising plume,
  - promote natural venting and mixing due to hot exhaust gas plume,
  - reduce H\textsubscript{2} accumulation in stagnation zones,
  - reduce the extent of the ceiling layer above the release location.
RESULTS

Mitigated Scenario

- Effect of PAR size
  - Similar effect on the formation of flammable clouds due to enhanced mixing, but different integral recombined mass for the three concepts.
  - PAR units 1 and 2 mounted in the flow path of the hydrogen plume significantly contribute to the reduction of hydrogen concentration and thus the overall risk.
  - The capacity of a large PAR units is not fully exploited.

- An increased and more evenly distributed number of small PAR units may be more efficient in terms of hydrogen removal and mixing. Furthermore, the positioning of a small PAR unit is easier to realize and more flexible compared to a large one.

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SUMMARY AND CONCLUSIONS

- An accidental release of $\text{GH}_2$ into the room of the propulsion system of a $\text{LH}_2$ carrier was investigated.
- Full-scale CFD model for analysis of H2 mixing and mitigation by passive auto-catalytic recombiners was developed.
- A PAR concept was designed on basis of an unmitigated reference case: PARs were implemented along the flow path of the $\text{H}_2$ rich plume and in the stagnation zone where an accumulation could occur.
- PARs reduce risk considerably by converting $\text{H}_2$ and promoting mixing.
- For further system optimization, use of small and more evenly distribute units is suggested.
- Future work should address the impact of ambient boundary conditions on the natural circulation mixing to support a generalization of conclusions.
- Ongoing work on model transfer to open-source CFD package containmentFoAM.