Rapid High Pressure LH$_2$ Refueling for Maximum Range and Dormancy

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Overview

Timeline
- Start date: October 2010
- End date: September 2013

Barriers
- C. Reliability and cost of LH$_2$ pumping

Budget
- Total project Value: $2.4M
  100% Complete
- Cost share percentage: 0%

Partners
- Linde 875 bar LH$_2$ pump supply, operation & maintenance
- BMW thermal insulation, performance requirements, automotive perspective
Relevance: \( \text{H}_2 \) refueling is limited by onboard heating and power & capital at the station

High pressure \( \text{LH}_2 \) pump resolves refueling challenges due to upstream liquefaction and no onboard cooling

**LH\(_2\) pump provides rapid fueling**
- Pump provides flow rate of 100 kg\( \text{H}_2 \)/hour
- Refuel time decoupled from compression heating

**Pressurized \( \text{LH}_2 \) refueling has high density and low power use**
- The pump starts with high density \( \text{LH}_2 \)
- Moderate compression (70 to 90 g\( \text{H}_2 \)/L)

**High pressure \( \text{LH}_2 \) pump makes cryogenic refueling practical**
- \( \text{H}_2 \) (at up to 70 K) sent rapidly to cryogenic vessel
- Negligible impact on station boil-off (1-3% of fill)
- Refuel onboard system of any temperature
- Can refuel adsorbents or ambient storage
Relevance: LH$_2$ is compressible with very moderate heating

LLNL fill model predicts 88.5 gH$_2$/L onboard at 875 bar using 300 bar experimental data from BMW

- 14 gH$_2$/L at 45 K
- 72 gH$_2$/L at 54 K
- 88.5 gH$_2$/L at 72 K
Approach: Verify LH$_2$ pump performance up to 350 bar

Determine 1) LH$_2$ fill time, 2) onboard density, 3) refueling efficiency, and 4) LH$_2$ pump boil-off

LLNL experimental system upgraded for 350 bar refueling and venting through Dewar stack
Accomplishments: Site preparation and pump installation

Electrical, civil, and mechanical work necessary for LH$_2$ pump & Dewar operation completed in 4 months
Accomplishment: Measure pump performance at 350 bar delivery (onboard refueling)

We have conducted eleven 350 bar vessel fill experiments for initial conditions from 288 to 21 K

Solid lines: Experimental results. Dotted lines: Predicted performance

- 5.1 min, 7.3 kg, 10 kWh<sub>e</sub>
- 4.4 min, 5.7 kg, 8 kWh<sub>e</sub>
- 6.5 min, 8.8 kg, 11 kWh<sub>e</sub>
- 6.5 min, 4.4 kg, 7 kWh<sub>e</sub>
- 5 min, 2.2 kg, 6 kWh<sub>e</sub>

Uninsulated fittings

151 L vessel initially at 288 K
Accomplishments: Measure pump performance at 350 bar delivery (onboard refueling)

We have conducted eleven 350 bar vessel fill experiments for initial conditions from 288 to 21 K

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Initial T K</th>
<th>Initial Pressure bar</th>
<th>Initial density g/L</th>
<th>Final T K</th>
<th>Final pressure bar</th>
<th>Final density g/L</th>
<th>H₂ mass pumped kg</th>
<th>Refuel time minutes</th>
<th>Average flow rate kg/hr</th>
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<th>Refuel energy kWh</th>
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Points in blue are within 2-phase region

Average measured efficiency: 96% (electricity/LH₂ out)
Maximum refuel pressure: 350 bar (vessel-limited)
Maximum flow rate: 111 kg/hr
Accomplishment: Inferred pump boil-off during operation

Thermodynamic analysis of Dewar mass vs. pressure data reveals near zero pump boil-off rate when dispensing H\textsubscript{2} at 350 bar

Data from pump acceptance test (10/15/2012, Linde, Germany)
Responses to reviewers’ comments

The project too closely replicates the work of BMW: BMW is producing a commercial product that may succeed in the market due to longer driving range, improved safety, and rapid refueling. LLNL is researching (1) The thermodynamics and behavior of H₂ at superliquid (70+ g/L) densities, (2) The viability of improvements to high pressure (>350 bar) cryogenic H₂ storage, (3) Thermomechanical lifecycle & strength testing with cryogenic H₂, and (4) High pressure (875 bar) cryogenic refueling station performance and durability

This project should add specific technology gaps and a cost model. Analysis of technology gaps and potential led to the proposed project. Argonne has conducted extensive cost modeling revealing that cryogenic pressurized storage has lowest cost of ownership. We are planning to work with Argonne to develop accurate cost models

The project should add a variety of other FCEV manufacturers. Other OEMs have expressed interest in conducting experiments at LLNL and/or joining the project
Responses to reviewers’ comments

The Linde LH$_2$ pump has the potential of 1–3% hydrogen boil-off loss and additional boil-off from the LH$_2$ storage tank. A 3% loss has a significant detrimental impact on WTW energy efficiency and cost: Pump evaporation does not result in Dewar boil-off. Pump extracts LH$_2$ from Dewar, and returns a fraction of evaporated LH$_2$ back into Dewar. Dewar typically *depressurizes* when running at these conditions. Boil-off from Dewar is due to environmental heat transfer or LH$_2$ transfer during Dewar fill. This approach to hydrogen refueling results in a variable amount of hydrogen in the fuel tank at the end of refueling, depending on the temperature, pressure, and amount of hydrogen in the tank at the start of refueling. Vehicle owners may not accept this. H$_2$ density in cryogenic pressurized storage is self-regulated: Frequent drivers keep vessel cold and refuel to high density while infrequent drivers’ warm vessel reduces storage density. Self-regulated density minimizes H$_2$ venting for all users. Two cold refuels are sufficient to transition from minimum to maximum range during continuous driving.
Collaboration with global leaders

- **Linde**: World class cryogenics experience. Manufactures maximum efficiency LH$_2$ pump. Delivered first commercial system to BMW in 2009 (300 bar). Very cooperative, sharing detailed information throughout LH$_2$ pump development, construction and installation.

- **BMW**: Long standing collaboration with LLNL through cryogenic pressure vessel CRADA. Contributing technical information and expertise. Advancing cryogenic pressure vessel technology and preparing demonstration vehicles.
Challenges and barriers:
Demonstrating LH$_2$ pump technical performance leading to improved onboard H$_2$ storage targets

- *Demonstrate high refuel density & durability of LH$_2$ pump:* Need 80+ gH$_2$/L cold refuel density and no degradation after pumping up to 24 tonnes LH$_2$ over ~ 2 years
Proposed future work:
As a part of new Storage/Delivery/Techval project, characterize LH$_2$ pump performance to 700 bar

Generate LH$_2$ pump performance map by conducting multiple partial and total fills
Future work: LLNL will assist ANL develop cost models for cryogenic pressurized hydrogen storage and delivery

Liquid delivery has advantages over gaseous delivery

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<tr>
<th></th>
<th>LH2</th>
<th>GH2</th>
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<tbody>
<tr>
<td>Station capital investment</td>
<td>More favorable (with sizable demand)</td>
<td>Less favorable (high compressor/cascade capital)</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>Less favorable (high liquefaction GHG)</td>
<td>More favorable</td>
</tr>
<tr>
<td>Delivery logistics</td>
<td>More favorable</td>
<td>Less favorable</td>
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<tr>
<td>Other issues</td>
<td>Boiloff rate</td>
<td>Cooling to -40°C</td>
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<td>Can benefit from surplus liquefaction capacity</td>
<td>Tube trailers eliminate need for onsite storage</td>
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</table>
Summary: 875 bar LH$_2$ pump can refuel onboard H$_2$ storage rapidly, efficiently, and to very high densities

- $H_2$ fueling limited by onboard heating, forecourt power & capital
- LH$_2$ pumping offers fundamental thermodynamic advantages: maximum refueling density, lowest theoretical refueling work, refueling speed not limited by heating
- Pump installation complete, experimental vessel and refueling hose ready: Commissioning in early July 2013, first refuel experiments in early August 2013
- Planned experiments characterize key aspects of LH$_2$ pump: $H_2$ flow rate, efficiency and boil-off
- Need higher pressure vessel (875 bar) to test full pump capability: flow rate, evaporation rate, maximum refuel density