Liquid Hydrogen Distribution Technology
HYPER Closing Seminar
Lutz Decker
Brussels, December 11, 2019
Agenda

1. Linde’s Product & Service Portfolio for Liquid Hydrogen Distribution
2. LH₂ / GH₂ Distribution and Storage
3. Linde manufacturing - LH₂ Products
4. HRS - LH₂ Fueling Station
5. Conclusion & Outlook
Linde’s Hydrogen Value Chain for H₂ Mobility
Linde Covers the Full Value Chain!

Production
- Conventional (e.g. SMR)
- Renewable (e.g. electrolysis)
- Onsite electrolysis

Distribution & Storage
- LH₂ liquid hydrogen
- CGH₂ compressed gaseous hydrogen
- Liquefaction

H₂ Fueling Stations
- Cryopump
- Ionic compressor
- Boil-off mgmt. system
- Dispenser

Infrastructure & Vehicles
Out of one hand
Reliable operations of H₂ supply and fuelling equipment to a range of mobility applications

1/7/2020 Latest Global Trend in Liquid Hydrogen Production, L. Decker, HYPER, Brussels
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Physical properties of hydrogen
Transport & storage – density differences
Liquid and gaseous hydrogen
Comparison of energy density

- Hydrogen in its liquid form allows a significant reduction of the storage footprint!
- Total weight of the equipment and supporting structures are equally reduced.
- Rule of thumb: gaseous hydrogen requires 4 time more footprint than liquid

➔ Where size & weight matter, liquid Hydrogen offers benefits.
How to supply Hydrogen?
LH$_2$ versus CGH$_2$

<table>
<thead>
<tr>
<th>consumer</th>
<th>close &lt;250 km</th>
<th>far &gt;250 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>small</td>
<td>CGH$_2$</td>
<td>CGH$_2$ / LH$_2$</td>
</tr>
<tr>
<td>large</td>
<td>CGH$_2$ / LH$_2$</td>
<td>LH$_2$</td>
</tr>
</tbody>
</table>

"Small consumer" means:
~100-200 kg/day
### Liquid and gaseous Hydrogen
Comparison of logistical aspects

<table>
<thead>
<tr>
<th>Method</th>
<th>Facts</th>
<th>+ Pros</th>
<th>- Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGH₂ Trailer</td>
<td>- Transport at 20MPa &amp; above</td>
<td>- Economical transport for short to medium distances</td>
<td>- Comparatively low capacity (high delivery frequency)</td>
</tr>
<tr>
<td></td>
<td>- Capacity: ~900kg</td>
<td></td>
<td>- Comparatively large on-site footprint</td>
</tr>
<tr>
<td></td>
<td>- Time to fill: 4 hours</td>
<td></td>
<td>- Residual gas in trailer (=waste)</td>
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<tr>
<td></td>
<td>- Time to off-load: 45 minutes (tube trailer swap!)</td>
<td></td>
<td>- the higher the pressure in the supply chain, the higher the amount/tonnage of CGH₂ in circulation!</td>
</tr>
<tr>
<td>LH₂ Trailer</td>
<td>- Transport at -253°C</td>
<td>- Economical transport for medium to long distances</td>
<td>- Comparatively high energy demand (~10kWh/kg for liquefaction)</td>
</tr>
<tr>
<td></td>
<td>- Capacity: ~4,000kg</td>
<td>- Comparatively small footprint</td>
<td>- Some liquid needs to remain in the distribution equipment to keep it cryogenic cold during return to the LH₂ source!</td>
</tr>
<tr>
<td></td>
<td>- Time to fill: 4 hours</td>
<td></td>
<td>➤ usable volume: ≤ 90%</td>
</tr>
<tr>
<td></td>
<td>- Time to off-load: ~1.0 hour (tube trailer swap!)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH₂ Container</td>
<td>- Transport at -253°C</td>
<td>- Economical transport for medium to long distances</td>
<td>- By remaining at customer site, 1x LH₂ transfer can be avoided ➤ less boil-off!</td>
</tr>
<tr>
<td></td>
<td>- Capacity: ~3,000kg</td>
<td>- Comparatively small footprint</td>
<td>- Overseas transport possible</td>
</tr>
<tr>
<td></td>
<td>- Time to fill: 3 hours</td>
<td></td>
<td>- Longer holding times possible (LIN shield)</td>
</tr>
<tr>
<td></td>
<td>- Time to off-load: ~0.5 hours (container swap!)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1/7/2020  Liquid Hydrogen Distribution Technology, L. Decker, HYPER, Brussels
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Linde Engineering, Schalchen Plant in Germany
The Manufacturing Facility for Cryogenic Equipment!

— Location: about 100 km east of Munich

— 25 workshops, large indoor manufacturing area (~65,000m²)

— All necessary disciplines available: engineering, sales & production, etc.

— High-quality materials only: Aluminum & Stainless Steel
Linde Manufacturing – Product Portfolio
Vast experience in the field of cryogenic plant equipment!

**Custom engineered Products**
- Brazed Aluminum HX & Cold boxes
- Coil-wound HX

**Standardized Products**
- Spirally-welded Aluminum Pipes
- HELICS™ & HYLICS™
- Vaporizers
- Cryogenic Storage Tanks

Liquid Hydrogen Distribution Technology, L. Decker, HYPER, Brussels
Liquid Hydrogen Tanks – Examples
Design for Industrial Applications

Key Data
— Inner volume: 71 m³ (references up to 270m³)
— Design pressure: 12 bar(g)
— Storage capacity: 4,600 kg LH₂ (1bar, 5% ullage)
— Vacuum-perlite insulation
— Integrated cryogenic valves
— Designed for industrial applications with high demand (electronics, chemical, etc.)
— Horizontal & vertical design

Performance
— Boil-off ratio: <44 kg/day (<0.95%/d)

Applications
— Typical industrial applications with high Hydrogen demand
Liquid Hydrogen Tanks – Examples
Optimized Design for Fueling Stations

Key Data
- Inner volume: 11.5 m³
- Design pressure: 6 bar(g)
- Storage capacity: 900 kg LH₂ (1bar, 5% ullage)
- Special integrated cryogenic valves
- Multi-layer insulation inside vacuum space
- Especially designed to fit into a 40ft container, and for fueling stations

Performance
- Boil-off ratio: <5.5 kg/day (<0.6%/d)

Applications
- Fueling stations, with low to medium Hydrogen demand
Liquid Hydrogen Tanks – Examples
Special Design for extremely low Boil-off!

Key Data
- Inner volume: **6,000 liters**
- Design pressure: **12 barg**
- Storage capacity: **400 kg LH₂** (1 bar, 5% ullage)
- Special integrated cryogenic valves
- Special insulation material inside vacuum space
- All necessary connections for LH₂ pump

Performance
- Boil-off ratio: **<2 kg/day** (<0.5%/d)

Applications
- Fueling stations, with low Hydrogen demand (tank for the early market phase)
Liquid Hydrogen Tanks – Examples
Larger Capacities for Bulk Storage

Key Data
— Inner volume: 300 m³
— Design pressure: 3.5 barg
— Storage capacity: 19.3 t LH₂ (1bar, 10% ullage)

Performance
— Boil-off ratio: <58 kg/day (<0.3%/d)

Spherical Tanks: Key Data
— Inner volume: 1100 - 2300 m³
— Design pressure: 2.6 barg
— Storage capacity: 70.2 – 145 t LH₂ (1bar, 10% ullage)

Performance
— Boil-off ratio: <70 - 145 kg/day (<0.1%/d)
**Linde Liquid Hydrogen Container**

**HYLICS™**

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### Key Technical Data

<table>
<thead>
<tr>
<th>Frame Size</th>
<th>40ft Container</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>UN Portable Tank</td>
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<tr>
<td>Design Pressure</td>
<td>12 bar(g)</td>
</tr>
<tr>
<td>LH2 capacity</td>
<td>3,000 kg (5% ullage)</td>
</tr>
<tr>
<td>Option</td>
<td>LIN-Shield</td>
</tr>
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</table>
Linde Liquid Hydrogen Trailer
More Tons of LH₂ on the Road!

Key Technical Data

<table>
<thead>
<tr>
<th>specification</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel length</td>
<td>13.7 m</td>
</tr>
<tr>
<td>Approvals</td>
<td>TPED / ADR 6.8</td>
</tr>
<tr>
<td>Design Pressure</td>
<td>12 bar(g)</td>
</tr>
<tr>
<td>LH₂ capacity</td>
<td>~4,000 kg (5% ullage)</td>
</tr>
<tr>
<td></td>
<td>No LIN-Shield</td>
</tr>
</tbody>
</table>
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Physical properties of hydrogen
Ideal compression work – pump – vs - compressor
Performance

- Footprint: 6.10 x 3.40m
- Capacity: Up to 50kg/hr.
- Bulk storage capacity: 400kg LH₂
- MAWP: 100 MPa
- Energy consumption (total): 45kW
- Specific energy consumption: 1.2 kWh/kg H₂ → Energy saving of ~ 70% ¹
- Boil-off: 4 kg/day, utilized for stand-by cooling
- Refueling protocol: SAE J2601-A70 and CEP
- Refueling performance: 6 FCEV cars/hr.
- Consequent development for installations at existing gasoline/ diesel retail stations, based on joint workshops with oil companies Shell, Total, OMV

¹ Compared to a conventional piston compressor
Cryogenic piston pump
How it works

Special design provisions:
- Super insulated Design
- Frequency drive (up to 4 Hz)
- Pump immersed in liquid hydrogen
- Double stage compression with LH₂ feeding piston
System function
Type CP 3.0

LH₂-Tank

Buffer storage (1000 bar)

To vent

CGH₂- Dispenser 700 bar

Electro-HE

Thermo-management

Dispenser line

Cryo Pump

Boil-off

Cryogenic Pump

-253°C

-220°C

-210°C

-40°C

-150°C

-100°C

-40°C

-20°C

-0°C

0°C

100°C

200°C

300°C

400°C

Temperature sensor
Flow sensor
Valve
Heat exchanger

Liquid Hydrogen Distribution Technology, L. Decker, HYPER, Brussels
Liquid hydrogen fueling station
Installation of type CP90 in Munich, Germany

Key Features

- Start of operation: Q2/2017 and Q3/2017
- Dispensing lines: 1x 70 MPa PV
- Technology: Cryo pump CP90
- Main user: CEP fleet, FCEV passenger cars
- Small footprint than CNG station
- 400kg LH$_2$ storage; equivalent to 40,000km of driving

Installation in central city locations, close to private houses and apartments
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Conclusion & Outlook

Drivers
— Regulations and policies will continue to change the energy mix and will require a reduction of emissions in the various modes of transportation.
— Hydrogen & Fuel cell technology has a set of advantages over other zero emission technologies.

Liquid Hydrogen
— LH₂ is not a “one-size-fits-all” solution, but is most efficient especially for larger FC power units, typically required for ships, energy storage systems, trains, etc.
— Supply chains for LH₂ have to be well thought-through, in order to reach an optimum between CAPEX and OPEX.

Next steps and key success factors
— Our innovations will focus on:
  — High-performing mobile & stationary LH₂ distribution equipment to make transportation and loading/unloading as simple as possible
  — Minimization of boil-off losses over the complete supply chain, incl. CAPEX/OPEX considerations
Thank you for your attention.

Making our world more productive
Linde’s Hydrogen Value Chain for H₂ Mobility
Liquid Hydrogen Fueling Station Type “CP90”

https://youtu.be/PJhc39S2deK