Metal hydride hydrogen storage tank for fuel cell utility vehicles

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Fuel cell utility vehicles (incl. forklifts): Motivation

Hydrogen powered utility vehicles including material handling units with fuel cells combine the advantages of diesel / LPG and battery powered vehicles:

- Constant power during the entire shift;
- Short refuelling time;
- Zero emission electric propulsion.

Metal hydrides for heavy-duty FC powered utility vehicles incl. forklifts: Motivation

**CGH2**
- Approved technology, prototypes available (Plug Power, H2Logics, Proton Motor, Pearl Hydrogen);
- Fast refuelling;
- Safety and refuelling infrastructure (filling H₂ pressure ~350 bar);
- Space constrains;
- Additional counterbalance required (forklift operation safety).

**MH**
- Compact + heavy: intrinsic solution of the counterbalance problem;
- Safety (lower standby H₂ pressure);
- Simpler refuelling infrastructure (filling H₂ pressure <200 bar);
- Limitations of charge / discharge rates (heat transfer issues).

Background: MH hydrogen storage on-board fuel cell utility vehicles

- Low weight H₂ storage capacity in MH is not drawback but advantage for this application.
- Main challenge of conventional solutions (MH containers in a water tank) is still insufficient system weight / too big size of the H₂ storage system.

- The MH tank (L=470 mm; W=700 mm; H=370 mm) stores ~2 kg (20 Nm³) H₂ and has a weight ~500 kg when filled with water.

- For sufficient counter-balancing, all the components are assembled within rectangular metal casting body, and the most of its internal volume was occupied by the MH tank.

Prototype FC power module with integrated MH hydrogen storage (Hawaii Hydrogen Carriers)

FC powered mine locomotive with integrated MH hydrogen storage (Vehicle Projects, Inc. & Anglo American Platinum)
In 2012-2015, HySA Systems integrated a MH $\text{H}_2$ storage extension tank in a commercial GenDrive 1600-80CEA fuel cell power module (Plug Power Inc.) which was installed in a 3 tonne STILL electric forklift.

Main performances (VDI-60):
- Energy consumption 11.15 kWh/h.
- $\text{H}_2$ fuel consumption 689 NL/kWh (CGH2 31%, MH 69%).

The prototype is in operation at Impala Platinum refineries in Springs, South Africa, since September 2015.

MH extension tank: details

- Assembly of 20x MH containers connected in parallel to gas manifold.
- The assembly is submersed in external water / glycol tank providing thermal control during the charge (cooling with ambient air) and discharge (heating from the FC stack).
- Dimensions 950 (L) x 120 (W) x 700 (H) mm; weight ~200 kg.
- The tank is fitted in the forklift in the space remaining vacant after the installation of the GenDrive power module.
- The total weight of the power module and the extension tank is ~1800 kg that provides sufficient counter-balance for the safe forklift operation when lifting up to 3 tons.
- Only minor changes in high-pressure H₂ system of the GenDrive power module.
- 21 Nm³ H₂ total capacity at charge pressure of 185 bar (for CGH₂ only ~19 Nm³ @ 350 bar).

Next step: full integration of the MH H₂ storage in fuel cell power module.
HySA Systems power module for forklift: concept

Fuel supply
Air supply
FC cooling
MH heating/cooling
BoP design

- The BoP designed around Ballard 9SSL / 75 Cell FC Stack.
- Main subsystems include:
  - The Cathode, Air Subsystem;
  - The Anode, H₂ Subsystem;
  - The Closed Circuit Water cooling (stack) / heating (MH) subsystem.
- Challenges:
  - Component selection constraints (availability, functionality & performance, size);
  - Insufficient weight (ballast required);
  - Alignment of the communication protocols
Stack cooling / MH heating system

- Stack cooling system is coupled with the system of heating the MH tank

Patent ZA 2014/08640
Gas supply system

- CGH2 buffer tank(s) provide stable H₂ supply during the FC operation (H₂ purging impulses)

*Patent ZA 2014/08640*
HySA Systems power module for forklift: Specification and preliminary design

- **Stack**: closed cathode FC;
- **H₂ storage**: integrated MH storage unit, 20 Nm³;
- **Battery bank**: deep cycle lead-acid, 8…10 kWh.

- **Donor vehicle**: STILL RX60-30L;
- **Bus voltage (VDC)**: 80;
- **Output power (kW)**: ~15 (average), up to 30 (peak);
- **Dimensions (mm)**: 840 (L) x 1010 (W) x 777 (H);
- **Weight (kg)**: 1800…1900

- The total weight of the power module ~650kg. Addition of 1150 kg of a ballast is required to achieve the target weight.
- The size of the MH bed and water tank is almost 40% of the total space in the power module compartment. CGH₂ buffer tanks do not fit in the available space.
HySA Systems power module for forklift: Updated design

- Fuel Cell Stack
- Anode Humidifier
- MH Bed Encased in Lead
- Cathode Heat Exchanger
- Air Intake Filter
- Compressor Motor Drive
- Cathode Air Compressor
- System Control Electronics
- H2 Recirculation Pump
- H2 Reducer
- Cooling Radiator and fan
- 8.4 kWh SLA Battery Bank
- MH Bed Encased in Lead
MH hydrogen storage: material

➢ C-14 AB₂-type intermetallics; A=Ti+Zr, B=Mn+Cr+Ni+V+Fe

Alloy 1: imported from CN (custom order)

Alloy 2: manufactured by HySA Systems

\[ Ti_{0.55}Zr_{0.45}(Cr,Mn,Fe,Ni)_2 + 10 \text{ wt}\% \ La_{0.8}Ce_{0.2}Ni_5 \]

\[ Ti_{0.85}Zr_{0.15}(Mn,V,Ni,Cr,Fe)_2 \]
MH hydrogen storage: container

- Standard SS pipe with pressed-in perforated copper fins
- Addition of expanded natural graphite to the MH powder
- Rated up to 190 bar / 100 °C
- External heating / cooling

Patent application WO 2015 189758 A1; patent ZA 2016/08250

H₂ charge performance

Alloy 1 (3.1 kg): 503 NL H₂
Alloy 2 (2.9 kg): 624 NL H₂
Main challenge of conventional solutions (MH containers in a water tank) is insufficient system weight.

Suggested approach: assembly of cassettes each comprising several MH containers encased in lead.

Patent application UK1806840.3; 26.04.2018
MH hydrogen storage: tank

- Special procedure of lead encasing which allows to simultaneously activate the MH material in the MH cassette has been developed.
- When heated with running water to $T=40–50\, ^\circ C$, the cassette releases more than 60% of its full capacity ($\sim 2.5 \, \text{Nm}^3$) at the $\text{H}_2$ flow rate of 25 NL/min.
- 8 MH cassettes have been manufactured and installed in the frame of forklift power module to form, together with 9L buffer cylinder, a hydrogen storage tank.
- The tank is characterised by $\text{H}_2$ storage capacity above 20 Nm$^3$ (1.8 kg) and has a weight $\sim 1.2$ tonnes that allows to provide counterbalancing weight (1850 kg for the whole power module within the space constrains) necessary for the safe operation of 3 tonne forklift.
- The tank can provide $>2$ hour long $\text{H}_2$ supply to the FC stack operated at 11 kWe ($\text{H}_2$ flow rate of 120 NL/min).
- The refuelling time of the MH tank ($T=15–20\, ^\circ C$, $P(\text{H}_2)=150–180$ bar) is about 15–20 minutes.

Left: two ready-to-use MH cassettes. Right: MH tank for forklift power module comprising 8 MH cassettes

$\text{H}_2$ charge (left) and discharge (right) performance of the MH cassette; water flow ($T=T(\text{in})$) $\sim 4$ L/min
FC power module: Assembling on-board prototype

- Optimised BoP configuration (FC stack + SLA battery pack + supercapacitors) and control algorithms.
- Integration of the heating circuit of the MH tank with the stack cooling system.
- Optimisation of the fuel supply and purging strategy to reduce H₂ consumption and increase efficiency is in progress.
Conclusions

• The use of fuel cells in heavy duty utility vehicles, including material handling units / forklifts or underground mining vehicles, has a number of advantages over similar diesel / LPG or battery-driven vehicles.
• Most of vehicular FC power systems have utilised compressed H\textsubscript{2} stored in gas cylinders at pressures up to 350 bar. This solution, however, results in too light weight of the FC power modules for the utility vehicles which require additional ballast for a proper counterbalancing to provide vehicle stability.
• Intermetallic hydrides with H storage capacities below 2 wt\% can provide compact H\textsubscript{2} storage simultaneously serving as a ballast. However, further weight increase is necessary for the sufficient counterbalancing within strict space constrains.
• New engineering solution of a MH hydrogen storage tank for FC utility vehicles which combines compactness, adjustable high weight, as well as good dynamics of hydrogen charge / discharge has been developed.
• The developed MH tank comprises plurality of MH cassettes made as assemblies of externally heated / cooled MH containers staggered together with the heating / cooling tubes and encased in molten lead followed by the solidification of the latter.
• The MH tank has been successfully integrated in a prototype fuel cell power module for electric forklift.
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