A novel hydrogen storage system for a RX60-30L 3-tonne electric forklift (STILL), equipped with a GenDrive 1600-80A fuel cell power module (Plug Power) has been developed. The system combines a compressed H2 composite cylinder (CGH2) and a liquid-heated-cooled metal hydride (MH) extension tank which is thermally integrated with a power module. The MH extension tank comprises a MH bed formed according to an advanced solution to provide easy activation of the MH material and fast H2 charge/discharge. The system has the same hydrogen storage capacity (~19 Nm3 H2 or 1.7 kg) as the separate CGH2 tank charged at P = 350 bar, but at a lower H2 charge pressure (<185 bar). A 15 min cycle refuelling provides the forklift with full-load operation (according to VDI-60 protocol) during >3 h, or 2 to 4 working shifts in a real industrial environment. The work also presents a hydrogen refuelling station (dispensing pressure up to 185 bar) with integrated MH compressor which has been developed for forklift refuelling.
Recently, fuel cells and batteries have been considered as counterparts of advanced hybrid energy storage systems, rather than competing technologies [2].

Currently, the use of Proton Exchange Membrane fuel cells (PEM FC) in the transportation sector is of great interest worldwide for the R&D sector, industry, business and public structures. PEM FC have a number of attractive properties, including low environment impact (only by-products are pure water and heat), high efficiency, low operating temperature, high power density, fast start-up time and response to load changes, simplicity, long life etc. As a result of these promising attributes, PEM FC have been successfully demonstrated in various applications, including: automobiles, scooters and bicycles, golf carts, utility vehicles, distributed power generation, backup power, portable power, airplanes, boats and underwater vehicles [3].

A brief overview of PEM FC powered electric vehicles, with peak power varying from <0.4 to 40 kW, was published by the authors in 2013 [4]. Due to non-uniform power consumption during operation, when the peak power can be significantly higher than the average one, the vehicular power systems usually have a “hybrid” layout. In doing so, the FC stack rated power is close to the average system power, and the peak power consumption by vehicle motors, as well as the quick start-up of the system, are provided by batteries and/or supercapacitors. Apart from the rated power and power train layout, the main distinguishing features of the vehicular power systems include: (i) vehicle bus voltage, (ii) type of the fuel cell stack (either liquid or air-cooled), and (iii) hydrogen storage method (compressed gas or metal hydride).

In the development of PEM FC vehicles special attention is paid to materials handling units/forklifts which have been identified as a promising early market for the fuel cell industry. In comparison to battery powered forklifts, fuel cell powered forklifts are characterised by lower total logistics costs as they require shorter refuelling time and less maintenance.

A detailed market analysis of the implementation of fuel cells for forklift applications was presented by Eigowainy et al. [5] in 2009 and, more recently, Larriba et al. [6] and Ramsden [7] in 2013. During the past decade the fuel cell forklift market has been growing, especially in the USA and Canada, with almost 3000 fuel cell forklifts deployed by 2013 [6]. Between 2003 and 2015, there were more than 6200 fuel cell powered forklift installations in the USA, including almost 1800 in 2014, of which most (>93%) involved PEM FC power systems [8]. Plug Power, Inc. controls more than 85% of the materials handling fuel cell market while other US companies, including: Oorja Protonics, Infintium Fuel Cells, and Nuvera Fuel Cells share the remaining 15% of the market [9]. It has been shown that even with the high costs associated with fuel cell systems and, particularly, the accompanying hydrogen refuelling infrastructure, a deployment of about 60 fuel cell forklifts for 2–3 shifts per day, 6–7 days per week will result in a lower total cost of ownership than comparable battery forklifts [7].

Information relating to the performance of PEM FC power modules for electric forklifts is available in the documentation issued by the OEMs: Plug Power, Inc. (USA) [10,11], Hydrogenics (Canada) [12], H2Logic A/S (Denmark) [13], and Infintium Fuel Cell Systems, Inc. (USA) [14].

An example of development and testing of a hybrid drivetrain, comprising a 16 kW PEM FC system, ultracapacitor modules and a lead-acid battery was published by Keränen et al., in 2011 [15]. Other recently published articles on PEM FC forklifts were focused on thermal and water management of the stack Balance of Plant (BoP) [16], performance simulation and analysis of a hybrid forklift power system (PEM FC + lead acid battery) [17], thermal and flow modelling of a PEM FC system for forklift applications over fast load changes [18] and numerical analysis of anodic recirculation in a PEM FC system for forklift applications [19].

Typical hydrogen-fuelled FC-powered forklifts are characterised by a fuel cell output power of about 10 kW, however, short peak power consumption can be as high as 50 kW for ~10 s. Such systems require a fuel capacity of about 20 Nm3 (1.79 kg) H2 to allow for uninterrupted operation at a rated load for several hours. Most of the FC-powered forklifts demonstrated so far have utilised compressed hydrogen stored in gas cylinders (CGH2) at pressures up to 350 bar, but in some cases metal hydride (MH) tanks were used [15,20,21].

MH technologies for hydrogen storage are characterised by compactness (due to the very high volumetric density of atomic hydrogen accommodated in the crystal structure of the MH matrix; 100 gH/L), intrinsic safety (originated from modest hydrogen equilibrium pressures at ambient temperatures in combination with the endothermic nature of hydrogen release from the MH), simplicity and flexibility [22–24]. Changing the component composition of hydride forming alloys allows for extremely wide variations in the thermodynamics of formation/decomposition of the corresponding MH: from −150 to −45 J mol−1 H2 K−1 for entropy and from −166 to −6.6 kJ mol−1 H2 for enthalpy [25]. Subsequently, MH hydrogen storage systems are characterised by tuneable pressure — temperature operating performances which can be aligned to the operating conditions of a specific application by appropriate selection of the type of MH and adjustment of the composition of the parent hydride forming material. In doing so, the low-grade heat (T ≤ 60–80 °C) released during low temperature (LT) PEM FC stack operation can be supplied to the MH, thus promoting the endothermic process of its decomposition and, in turn, H2 supply to the stack. This solution has been successfully verified in numerous portable, mobile and stationary LT PEM FC applications [26–29].

Hydrogen storage in MH is, therefore, a promising option which can efficiently solve on-board H storage problems. In spite of this, the low H storage weight density in commonly used “low-temperature” MH materials (~2 wt.% H) is considered as the main obstacle for their use in vehicular applications [23]. We note that such limitations relate to conventional vehicles like buses and passenger cars; and for utility vehicles, including light-duty industrial vans [26], underground locomotives and dozers [30], and materials handling units [15,20,21,31,32], this is not the case. Moreover, the utility vehicles should be heavy enough to provide a low centre of gravity.

An on-going development of a FC-powered forklift with MH hydrogen storage (USA [31,32]) can be mentioned as an example of such application. The system is expected to be superior to both battery-driven forklifts (shorter charge time,
longer lifespan) and to the FC-powered ones with CGH2 storage (simpler refuelling infrastructure, higher H2 storage capacity, less safety issues). The liquid heated/cooling MH hydrogen storage tank uses a composite MH material based on an AB5-type MnMnNi4.5Al0.5 alloy (Hy-Stor 208) which is characterised by a H absorption capacity up to 1.2 wt.% and H2 equilibrium pressure of ~20 bar at T = 75 °C [33]. The tank has dimensions 470 mm (L) × 700 mm (W) × 370 mm (H) and is designed as a staggered array of 40 tubular (Ø50.8 mm × 640 mm) MH containers connected to a common gas manifold and heated/cooling by circulating liquid. The heating/cooling system is directly integrated in the LT PEM FC coolant loop. The hydrogen storage capacity of one of these containers is estimated to be about 50 g H2, which yields approximately 2 kg (22.4 Nm3) H2 in total. Though test results of the H2 charge/discharge performance of the MH tank have not been presented yet, the H2 refuelling time at the pressure up to 70 bar was estimated (by modelling) as ~30–60 min. The refuelling dynamics, however, were found to be very sensitive to the rate of heat rejection from the coolant loop [32], resulting in significantly longer refuelling time at low (<50 bar) H2 pressures and high (>1 g/s) H2 flow rates.

The slow charge and discharge of MH hydrogen storage tanks, as a result of poor heat transfer, is a serious disadvantage of these systems and requires special engineering solutions to be overcome [33]. The H2 charge/discharge rates dramatically decrease with the size of individual MH containers; this effect can be mitigated by improving the effective thermal conductivity of the MH bed, as well as by the intensification of heat exchange between the MH and heating/cooling fluid [29]. Nevertheless, typical H2 charge times for large (~1 kg H2) MH containers equipped with heat exchangers, are usually not shorter than 90 min [34].

In addition to the technical and economic challenges hindering the commercialisation of hydrogen fuelled vehicles and, particularly FC forklifts, the lack of hydrogen refuelling infrastructure is also a significant problem [7]. Despite a certain number of hydrogen refuelling stations operating worldwide, they are not being introduced broadly enough. This is mainly as a result of their high costs; ranging between $500,000 and $5,000,000 per installation [35]. The most expensive H2 refuelling components originate from: (i) on-site hydrogen production and (ii) hydrogen compression. The latter problem can be effectively addressed by the application of MH for hydrogen compression driven by low-grade heat [24].

Summarising the above-mentioned, we can conclude that the development of fuel cell powered forklifts, with hydrogen storage based on metal hydride technologies, can be facilitated once the following challenges are addressed:

- Improvement of charge – discharge dynamic performances of on-board MH tanks;
- Safe, reliable and cost-effective hydrogen refuelling solutions.

This paper presents the results of work aimed at overcoming these issues. Specifically, it involves the development of MH-based hydrogen storage and supply/refuelling systems for a commercial electric forklift equipped with a LT PEM FC power module. The work was undertaken between 2012 and 2015 by HySA Systems Competence Centre in South Africa, with the involvement of two local industrial partners: Impala Platinum Ltd (the customer) and TF Design (Pty) Ltd (manufacturer of the hardware).

### Approach

A novel system concept for fuel cell powered utility vehicles with on-board MH hydrogen storage has been proposed by HySA Systems (Fig. 1). The system consists of:

- STILL RX60-30L electric forklift with a 3 tonne lifting capacity and 80 VDC bus voltage.
- On-board fuel cell power module (A) replacing the forklift battery. The module is equipped with:
  - compressed gas hydrogen storage tank (CGH2), and,
  - MH hydrogen storage tank (B).
- Stationary hydrogen refuelling system (C) consisting of a low-pressure hydrogen supply and a MH hydrogen compressor.

The main feature of the on-board hydrogen storage is a combination of the CGH2 and MH in a “distributed hybrid” system [36,37] consisting of individual MH and CGH2 tanks with a common gas manifold, and a thermal management system in which the MH tank is integrated within the cooling system of the LT PEM FC BoP. This solution allows for: (i) an increase in hydrogen storage capacity of the whole gas storage system and the reduction of H2 charge pressure; (ii) shorter charging times in the refuelling mode and smoother peaks of H2 consumption during its supply to the fuel cell stack; (iii) the use of standard parts with simple layout and lower costs; and (iv) adding flexibility in the layout and placement of the components of the hydrogen storage and supply system.

At the first stage of realisation of this concept we introduced a MH tank as an extension of the CGH2 storage (composite cylinder with a 74 L inner volume and operating pressure of 350 bar) in the commercial fuel cell power module, GenDrive 1000 160X-80CEA, purchased from Plug Power Inc. The objective of this was to achieve approximately the same hydrogen storage capacity (1.7 kg, or 19 Nm3 H2) at the lower refuelling pressure. The required amount of stored hydrogen should be provided in a reasonable refuelling time, no longer than 20–30 min, and the H2 supply to the fuel cell stack should be sufficient to provide its uninterrupted operation at the maximum rated power (~10 kW).

The MH tank uses a low-stability AB5-type MH material with a H2 equilibrium pressure above 10 bar at room temperature, which provides sufficient pressure driving force for the H2 supply to the FC stack during operation. In doing so, the endothermic effect of H2 desorption from the MH is compensated by its heating to a moderate temperature (~30–50 °C) using both environmental heat, as well as the heat

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1 Reference [36] is a patent application disclosing the technical details of this engineering solution while the detailed system study, including its integration in a light electric vehicle (golf cart) with PEM FC range extender, is presented in Ref. [37].
generated by the stack. In the charge mode, at H2 pressures between 100 and 200 bar the heat released due to the exothermic H2 absorption in the MH is dissipated to the environment. The presence of the CGH2 buffer allows for the thermal “recovery” of the MH in the discharge mode in the periods when H2 consumption by the stack drops. In addition, the CGH2 buffer also allows for the charge time to be shortened as a result of the accumulation of moderately high-pressure H2 in the gas phase, which is further absorbed in the MH as it is cooled down [37].

Hydrogen refuelling, therefore, requires H2 dispensing pressures lower than those typically used for the refuelling of CGH2 storage systems (350 bar). For industrial customers, who already possess low-pressure pipeline hydrogen, steam and cooling water, thermally-driven hydrogen compression using metal hydrides [24] is a promising option, allowing for significant reductions in refuelling costs. The high selectivity of hydrogen absorption/desorption in MH provides a high purity of the delivered H2, which allows for simultaneous hydrogen purification within the MH compressor. Since the refuelling has to be done periodically, the necessary amount of hydrogen at the pressure higher than the dispensing one can be stored in a high-pressure buffer, filled from the MH compressor when necessary.

Metal hydride tank

Metal hydride material

The systems use a MH material based on an AB2-type hydrogen storage alloy, where A = (Ti,Zr); B = (Fe,Cr,Mn,Ni) and the Ti:Zr atomic ratio is approximately 0.65:0.35. According to XRD studies (see Fig. 2 and Table 1 for details), the starting alloy consists of a single intermetallic phase (C14 Laves, MgZn2-type); the values for the hexagonal lattice periods (a, c) and unit cell volume (V) are presented in Table 1. Hydrogenation does not change the crystal structure but results in a lattice expansion, with a relative volume increase (ΔV/V0) of approximately 16%. The hydride, AB2Hx, is unstable at ambient conditions so the XRD pattern of the hydrogenated material (Fig. 1) also contains the lines of the solid solution of hydrogen in the parent intermetallic, AB2H~0, as a product of the hydride decomposition during the XRD measurements.

The XRD data allowed us to calculate the density (ρ) of the material in the hydrogenated state. This parameter is very important to provide a safe filling density of the MH in the containment, i.e., lower than 61% of the real density of the hydrogenated material [38].

Fig. 3 shows hydrogen sorption isotherms for the MH material. The experimental data taken for H2 absorption (filled symbols) and desorption (empty symbols) in the range between T = –25 °C to +75 °C and P = 0.1 bar–200 bar were further processed by the model of phase equilibria in metal–hydrogen systems [39]; the calculated isotherms at T = –25 to +125 °C are presented as lines. Due to the low hysteresis observed, the absorption and desorption data were processed together.

It can be seen from Fig. 3 that the selected MH material provides high enough H2 pressures (>10 bar) at temperatures above 0 °C, and at T > 125 °C most of hydrogen is desorbed at P > 200 bar. The results indicate that the MH is suitable for both hydrogen storage/supply and hydrogen compression applications, therefore, both the MH hydrogen storage...
extension tank and the MH compressor for the refuelling system for the LT PEM FC forklift use the same AB2-type MH material.

**MH container**

Preliminary modelling of the heat transfer performance in the MH reactors showed that the optimal layout of a medium-sized (Ø 60 mm × 500 mm) cylindrical MH bed is a combination of external heating/cooling with internal heat conductive fins. For copper fins (thickness 0.5 mm, pitch 5 mm) and intensive heat transfer between a heating/cooling fluid outside the reactor and a metal hydride bed in the reactor (overall heat transfer coefficient up to 800 W m⁻² K⁻¹), the charge time at a room temperature of the fluid can be as short as 10 min [40]. This layout was used in the design of the MH container for the hydrogen storage extension tank (Fig. 4).

The stainless steel container (Ø 51.3 mm × 800 mm; empty weight 5.7 kg) was filled with 3.2 kg of MH material (filling density 3.47 g/cm³, or ~60% of the material density in the hydrogenated state). The formation of the MH bed was achieved according to an in-house advanced solution [41], which provides easy activation of the MH material and fast H₂ charge/discharge due to the improved heat exchange between the MH material and the circulating liquid. Specifically, the solution involves the minor addition of an easily hydrogenated AB₅-type MH material, along with expanded natural graphite (ENG) to the main AB₂-type alloy. The latter also allowed us to achieve a MH filling density close to the maximum safe value (see above). The container comprises a number of perforated copper fins, 0.5 mm thick, firmly pressed into the cylindrical part of the container with a pitch of 5 mm. The gas pipeline in the container is ended by a plugged stainless steel porous filter (not shown; 6 mm in the diameter, 50 mm in the length, 1 µm pore size). The container is also equipped with a longitudinal gas bypass element, facilitating H₂ transfer along the MH bed.

Fig. 5 shows details and results from the testing of a prototype MH container, made according to Fig. 4, to evaluate its H₂ charge/discharge dynamic performance. The container was submersed in a water bath where a controlled temperature of 25–50 °C was maintained. The test rig (Fig. 5A) was also equipped with a pressure sensor, which enabled monitoring of the hydrogen pressure in the line, P(line), as well as mass flow controller for the measurement and limitation of the H₂ flow rate (FR). A specially designed gas distribution system allowed for switching the hydrogen flow to/from the container, thus providing a unidirectional hydrogen flow through the mass flow controller.

The prototype MH container was equipped with six ports for placing K-type thermocouples into for the measurement of temperature distribution in the MH bed during absorption/desorption. The location of thermocouple joints is shown in Fig. 5B. Four thermocouples (temperatures T₁ – T₄) were located in the middle of the container, while the other two were shifted from the middle by 158 mm towards the H₂ input/output pipeline (T₅) and in the opposite direction (T₆). The latter port (TC₆/T₆) was also equipped with a pressure sensor.

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**Table 1 – Summary of the XRD data.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parent alloy</th>
<th>Hydrogenated alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>a [Å]</td>
<td>4.9296(3)</td>
<td>4.9340(2)</td>
</tr>
<tr>
<td>c [Å]</td>
<td>8.0723(9)</td>
<td>8.0858(4)</td>
</tr>
<tr>
<td>V [Å³]</td>
<td>169.88(2)</td>
<td>170.475(9)</td>
</tr>
<tr>
<td>ΔV/V₀ [%]</td>
<td>–</td>
<td>0.35</td>
</tr>
<tr>
<td>ρ [g/cm³]</td>
<td>6.884</td>
<td>6.678</td>
</tr>
</tbody>
</table>

---

**Fig. 2** – The refined XRD pattern (Cu-Kα) of the hydrogenated AB₂-type alloy. Before the XRD measurements the hydride was stabilised by exposing to air at liquid nitrogen temperature. The pattern contains lines of the hydride, AB₂Hₓ, as well as of the solid solution of hydrogen in the parent intermetallic, AB₂H₀, formed during the hydride decomposition.

**Fig. 3** – Experimental (points) and calculated (lines) hydrogen sorption isotherms for the AB₂-type alloy. Curve labels show the temperatures [°C].
allowing for the monitoring of H₂ pressure in the container, P(container) at approximately 560 mm from the H₂ entrance/exit pipeline.

In addition to the temperatures within the MH bed (T₁ – T₆), the wall temperature of the container (T_w) was also measured.

As shown in Fig. 5C, the hydrogen absorption in the prototype container when the temperature of the circulating water is T₀ = 30 °C, H₂ line pressure is P₀ = 85 bar and maximum limit of H₂ flow rate is 40 NL/min, takes no longer than 15 min. In doing so, about 450 NL (40.2 g) H₂, or 88% of the separately determined maximum hydrogen storage capacity of the container (510 NL, or 45.5 g), is absorbed. The absorption is accompanied by heating of the MH bed, with the temperature differences, ΔT, between the corresponding point and the circulating water in the range from 12.5 to 17.5 °C. A general finding was that ΔT decreased with an increase of radial distance from the container axis and, to a lesser extent, the longitudinal distance from the H₂ input side. The temperature difference between the container wall and circulating water did not exceed 4 °C. Interestingly, it was found that at the beginning of the absorption process, higher temperatures of the MH bed (ΔT up to 20 °C) were observed. This may be a result of H₂ absorption in the small admixture of AB₅ alloy, characterised by a higher hydrogenation heat effect than the AB₂ one (~30 kJ/mol H₂ vs. ~20 kJ/mol H₂).

During H₂ absorption, the measured pressures in the MH bed, P(container), were found to be lower than the line pressure, P(line), gradually approaching the later value as H₂ absorption at the constant flow rate (40 NL/min) comes closer to the completion.

Fig. 5D shows an example of the test results in H₂ desorption mode. It was found that a stable H₂ supply from the MH container, whose temperature is maintained at the same level (T₀ = 30 °C), can be provided at a flow rate up to 10 NL/min. At the rated flow rate (about 7.5 NL/min per container) approximately 435 NL (38.8 g) of H₂ (85% of the maximum H₂ storage capacity) can be delivered. The absolute values of ΔT during the desorption mode are lower than for absorption and do not exceed 3–7 °C. A similar effect of higher |ΔT|, possibly due to the addition of the AB₅-type hydride, was observed at the end of desorption.

Taking into account the limitations on minimum hydrogen pressure on the high-pressure side of the hydrogen system in the GenDrive power module, P(min) = 13.5 bar, the amount of hydrogen available for the delivery from the MH tank will be lower, corresponding to 360 NL (32.1 g) H₂ or 70.5% of the maximum hydrogen storage capacity. This reduction can, however, be mitigated by the higher temperatures of the heating fluid additionally heated from the fuel cell module, as well as by the presence of CGH₂ buffer in the “distributed hybrid” hydrogen storage system.

**Tank assembly**

The metal hydride extension tank (Fig. 6) was made as an assembly of twenty MH containers (1) connected in parallel to gas manifolds (2) and, further, to a shut-off gas valve (3). The assembly is held by a cradle (4) submersed in an external water tank (5) providing thermal control of the MH containers during their charge and discharge.

The tank has dimensions 950 mm (L) × 120 mm (W) × 700 mm (H), weighs approximately 200 kg and is fitted within the forklift in the space remaining vacant after the installation of the GenDrive power module (labelled 1 in Fig. 7). Note that the total weight of the power module (1) and the extension tank (2) is about 1800 kg which provides sufficient counter-balance for safe forklift operation when lifting loads rated up to 3 tonnes.

The tank assembly (shown in Fig. 7) also includes a gas connector (2.1), in-line tee-type gas filter with pore size 0.5 μ (2.2) and a valve connected to the high-pressure hydrogen line of the power module (2.3). The thermal management system
of the tank also includes a diaphragm circulation pump (2.5; 18.9 kg/min at the head of 2.4 bar), and radiator (2.6) equipped with three axial fans (5500 rpm). The fans and circulation pump are powered (24 VDC, 210 W max) from the forklift side of power connector (1.1), via DC/DC converter and controller (not shown) and can be switched ON and OFF by the remote block (2.7).

The integration of the MH extension tank requires only minor changes to the high-pressure hydrogen system of the GenDrive power module, as shown in Fig. 8. The piping components of the MH tank are assembled using ¼” OD stainless steel tubing and include shut-off valves located inside (V1, 3 in Fig. 6) and outside (V2, 2.3 in Fig. 7) of the water tank, inline gas filter (F1, 2.2 in Fig. 7), and tee union (T1) where the main high pressure gas piping (3/8” OD stainless steel tubing) inside the power module is connected. The latter includes a hydrogen receptacle, check valve (CV1), and adapters (A1 & A2) installed in the gas manifold of the gas cylinder. The check valve (CV1) was moved from its original position in the gas cylinder (in place of adapter A1) to provide bidirectional gas flow between the cylinder and MH tank to improve the performance of the “distributed hybrid” hydrogen storage system [36,37].

Thermal management of the MH tank is provided by the circulation of a liquid (50:50 water – glycol mixture) using a circulation pump and radiator (labelled 2.5 and 2.6, respectively in Fig. 7). During charging, the forklift door is opened and the fans installed in the radiator (2.6) provide cooling (by the flow of ambient air) of the circulating liquid which is

Fig. 5 – Details (A, B) and results (C, D) of the tests of the prototype MH container for the hydrogen storage extension tank. A – experimental test rig; B – location of the thermocouple joints in the container; C – H2 absorption at P0 = 85 bar, T0 = 30 °C and maximum limit of H2 flow rate of 40 NL/min; D – H2 desorption at T0 = 30 °C and maximum limit of H2 flow rate of 7.5 NL/min.

Distances of thermocouple joints from the axis [mm]:
- TC1, TC5, TC6 (T1, T5, T6) 3
- TC2 (T2) 5.6
- TC3 (T3) 11.1
- TC4 (T4) 16.7
heated-up due to exothermic hydrogen absorption in the MH containers.

During operation of the forklift the door is closed, and the fans installed in the radiator (2.6) capture hot air (T~60 °C) from the cooling system of the unit (1) thus providing the heating of the MH containers which are cooled down due to endothermic hydrogen desorption.

The operation of the thermal management system is provided by the controller powered from the 80 VDC input power circuit of the forklift (output of the FC module), via remote display and control block (2.7).

**Refuelling station**

Figs. 9 and 10 show the layout and general view of the hydrogen refuelling station. The station includes the following components:

**Fig. 6** – Hydrogen storage containment of the metal hydride extension tank assembly. 1 – metal hydride containers, 2 – gas manifolds, 3 – shut-off valve, 4 – cradle, 5 – water tank.

**Fig. 7** – An overview of the on-board system. 1 – GenDrive 160X-80CEA power module, 1.1 – power connection to the forklift, 1.2 – gas cylinder manual shutoff valve, 1.3 – remote display and control block, 1.4 – refuelling receptacle, 1.5 – dewatering receptacle, 1.6 – communication connector; 2 – metal hydride extension tank, 2.1 – gas connector, 2.2 – gas filter, 2.3 – manual gas shutoff valve, 2.4 – water tank, 2.5 – circulation pump, 2.6 – radiator, 2.7 – remote display and control block.
Fig. 8 – Gas piping diagram of the MH extension tank integrated with GenDrive power module. V1, V2 – gas shut-off valves, F1 – gas filter, CV1 – check valve, T1 – union tee, A1, A2 – adapters for the connections to gas cylinder manifold.

Fig. 9 – General layout of the hydrogen refuelling station.
• **Hydrogen Dispenser**, integrated with a thermally driven metal hydride hydrogen compressor (MH Compressor), items 1 and 2 in Fig. 10;
• **Buffer Storage/Cylinder Pack**, item 3 in Fig. 10;
• **Control Block**, item 4 in Fig. 10;
• A console (item 5 in Fig. 10) holding hydrogen refuelling nozzle (H₂ Nozzle), connector for Water Removal, and earth clamp;
• **Ejector** for water removal (item 6 in Fig. 10);
• **Hydrogen Venting** pipeline, item 7 in Fig. 10.

Although the refuelling station is an experimental prototype, it complies with South African safety regulations for operation in a fire and explosion hazardous environment. As specified in Fig. 9, the main equipment of the refuelling system forms a hazardous area (Zone 2; Zone 1 for the end of the venting line) while the control panel, the console with refuelling nozzle, and the water removal connector, as well as the forklift itself, are located outside the hazardous zone.

The refuelling station utilises the following services supplied by the customer, Impala Platinum Refineries (Fig. 9; item 8 in Fig. 10):

- Low pressure hydrogen (40–60 bar), consumption up to 12 Nm³/h (1.07 kg/h);
- Low grade steam (130–150 °C), consumption up to 33 kg/h;
- Circulating cooling water (supply at ≤25 °C and return), consumption up to 15 kg/min;
- Instrument air (5.5–7.5 bar), average consumption below 1 NL/min, peak consumption up to 55.5 NL/min for no longer than 15 min;
- Electric power (525 or 230 VAC, single phase), consumption up to 2000 W max.

The necessary amount of dispensed hydrogen is provided by the Buffer Storage, a pack frame assembly of 18 gas cylinders, with a total (water) internal volume of 900 L and hydrogen storage pressure up to 200 bar. The buffer is connected to both hydrogen Dispenser and hydrogen compressor (MH Compressor), the latter maintains the maximum hydrogen pressure (195–200 bar) in the buffer during the operation of the hydrogen refuelling system.

The integrated hydrogen dispensing and compression unit provides one-stage compression of the low pressure (~50 bar) hydrogen to the high pressure (200 bar; throughput 7.5 to 12 Nm³/h) using an AB₂-type MH material (as described previously) and steam for the heating and water for the cooling. The high-pressure hydrogen is supplied to the Buffer Storage tank, and, further to the Dispenser which delivers hydrogen (controlled ramping 0–185 bar) to the dispensing H₂ Nozzle when refuelling of the forklift is necessary. The unit is also equipped with a vent pipeline for the safe release of hydrogen, as well as with the auxiliary pipelines for the purging of the gas systems with nitrogen to provide safety before and after installation and during servicing.

Independent automated operation of both hydrogen dispensing and hydrogen compression units is provided by the Control Block.

The developed hydrogen refuelling station is characterised by simplicity in design, operation and service; higher safety and reliability; noiseless operation, and lower capital and operating costs than existing high-pressure (350–700 bar) hydrogen refuelling stations available on the market. These benefits are due to:

- Lower hydrogen dispensing pressure (up to 200 bar) which enables the use of standard gas service components (fittings, valves, etc.);
- Relatively slow pressure ramping (5–15 min) which prevents overheating of the supplied H₂ and, thus, eliminates the requirement for deep cooling;
- The replacement of a mechanical hydrogen compressor with the metal hydride compressor which utilises waste industrial heat, instead of electricity, for the hydrogen compression.
The benefits specified above are particularly relevant for industrial customers who possess the necessary infrastructure, namely, low-pressure pipeline hydrogen, circulating cooling water and low-grade steam.

The 15 min refuelling cycle of the forklift with LT PEM FC power module and MH extension tank at the dispensing pressure 150–185 bar can provide its full-load operation (according to VDI-60 protocol) during more than 3 h. Depending on the operation schedule at the customer’s site, the forklift requires refuelling after its operation in the real industrial environment during 2–4 working shifts.

A forklift equipped with a PEM FC power module and a MH extension tank, along with a hydrogen refuelling station have recently been put into operation at Impala Platinum Refineries in Springs, South Africa as a result of this work. Results of the detailed field tests of the systems will be published elsewhere.

Conclusions

- This work describes a novel concept for the integration of MH in the H storage system on-board an electric PEM FC forklift by coupling a MH extension tank with a commercial PEM FC power module.
- The MH extension tank uses a low-stability MH, based on an AB2-type alloy, in combination with an advanced engineering solution for the MH container, to provide a high system dynamic performance.
- H₂ refuelling of the PEM FC forklift is provided by a novel low-pressure refuelling system, integrated with MH compressor.

Acknowledgements

This work is supported by the Department of Science and Technology (DST) within the HySA Programme (HySA Systems projects KP3-S02 and KP3-S03), and Impala Platinum Limited; South Africa. Investment from the industrial funder has been leveraged through the Technology and Human Resources for Industry Programme, jointly managed by the South African National Research Foundation and the Department of Trade and Industry (NRF/DTI; THRIP Project TP1207254249).

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