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Hydrogen refuelling station with integrated metal hydride compressor: Layout features and experience of three-year operation

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ABSTRACT

Hydrogen compression is a main contributor in the capital and operation costs of the H₂ refuelling infrastructure. The use of metal hydrides (MH) for thermally-driven H₂ compression can provide efficient solution to mitigate this challenge. MH compressors are particularly promising for industrial customers who possess necessary infrastructure including pipeline H₂, sources of low-grade heat, etc.

Here we present the details about layout of the H₂ refuelling station and its operation at Impala Platinum refineries in Springs, South Africa, since its start-up in September 2015. The station provides H₂ dispensing at the pressure up to 185 bar and uses pipeline H₂ (P = 50–60 bar) available at the customer site. H₂ compression to P = 200 bar with productivity up to 13 Nm³/h is provided by the integrated 1-stage MH H₂ compressor which uses steam (T~140 °C) for the heating and circulating water (T~20 °C) for the cooling; both steam and water are also available from the customer infrastructure. The station also includes H₂ dispenser, buffer tank (standard gas cylinder pack), and control block on the basis of Siemens Program Logic Controller (PLC) which provides fully automated system operation. Switching H₂ and steam/water flows is carried out with the help of remotely controlled, pneumatically actuated valves and auxiliary check valves. Additionally, at P = 200 bar the control block switches the system into standby mode when MH compression modules are cooled down and their gas manifolds are connected to the H₂ supply line. The H₂ dispensing is independent on the compressor operation and takes from 6 to 15 min. The refuelling station complies with South African safety regulations for operation in a fire and explosion hazardous environment.

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Introduction

Very high capital and operating costs of hydrogen refuelling infrastructure significantly hinder market adoption of fuel cell vehicles. The contribution of hydrogen refuelling stations was estimated as ~50% of the cost of hydrogen fuel at dispenser to be between USD 13 and 15 per 1 kg H₂ (California, 2017) [1–3]. Of the total investments in a less expensive H₂ refuelling station (150 kg H₂/day, truck-delivered H₂; USD ~600 000, Shanghai, 2007), about 60% relates to the infrastructure providing hydrogen storage, compression and purification [4]. Additional capital costs (10–11%) are necessary to provide hydrogen pre-cooling [1,2,5].

Hydrogen compression is a major contributor to the capital costs (48%) and maintenance hours (24%) of the H₂ refuelling stations [5]. Conventional use of mechanical H₂ compressors is associated with safety and reliability issues mainly related to the operation of moving parts and their seals under high hydrogen pressures (up to 400 and 900 bar for H₂ dispensing pressures of 350 and 700 bar, respectively). Relatively high energy consumption for H₂ compression, >15% of the lower H₂ heating value [6], results in high electricity costs which, together with the maintenance costs, are the main contributors to the operating costs of the hydrogen compression component of the refuelling infrastructure.

Metal hydride hydrogen compressors (MHHC), which use reversible thermally driven interaction of hydride forming metals and alloys with hydrogen gas are promising alternative to conventional mechanical compressors of hydrogen. The MHHC have a number of advantages including practically unlimited discharge pressure (up to several kilobars), scalability (from x L/h to x m³/h H₂), modular design, simplicity in service and repair, high purity of the released H₂. Except for some gas-distribution components (e.g. check valves), there are no moving parts (pistons, membranes) in the MHHC that results in the simplification of the design and the increase of operation reliability [7–10]. As compared to novel method of electrochemical hydrogen compression having similar advantages [11], MHHC do not require complicated sealing of H₂ compressing stack resulting in higher safety and reliability as respect to leaks at high H₂ pressures. MHHC also allow to utilise waste heat instead of electricity for H₂ compression and thus are very beneficial for industrial customers who have this resource in their possession [7–9].

In Refs. [12,13] we reported about development of metal hydride (MH) extension tank for fuel cell powered forklift, along with H₂ refuelling station with integrated MHHC. Due to presence of the MH component in the on-board hydrogen storage system, the H₂ dispensing pressure could be lowered from 350 to ≤185 bar without decrease of the useable hydrogen storage capacity (>1.8 kg) which was reached in a reasonable refuelling time (6–15 min). The above-mentioned publications were mainly focused on the layout of the on-board hydrogen storage system and performances of the forklift, and the features of the refuelling station (including the ones previously reported in Refs. [8,9]) were considered only briefly.

Here we present the details about layout of the H₂ refuelling station and its operation at Impala Platinum refineries in Springs, South Africa, since its start-up in September 2015.

Features

General layout and specification

The hydrogen refuelling station is intended for the refuelling of fuel cell forklifts at Impala Platinum Refineries at H₂ dispensing pressure up to 185 bar and ambient temperature.

Figs. 1 and 2 show the general layout and the images of the hydrogen refuelling station. The station includes the following components:

- Hydrogen dispenser (2) integrated with thermally driven metal hydride hydrogen compressor (1);
- Buffer hydrogen storage/gas cylinder pack (3);
- Control block (4);
- A console (5) holding hydrogen refuelling nozzle (5a), connector for water removal (5b), ejector for water removal (5c) and earth clamp;
- Hydrogen venting pipeline (6).

The refuelling station consumes the following services supplied by the customer (see Fig. 2, right):

- Low pressure hydrogen (50–60 bar, 99.99% purity, <1 ppm CO and CO₂), consumption up to 15 Nm³/h;
- Low grade steam (130–180 °C), consumption up to 33 kg/h;
- Circulating cooling water (supply at T ≤ 30 °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 not longer than 15 min;
- Nitrogen (for the purging H₂ systems before and after service works);
- Electric power (525 or 230 VAC, single phase), consumption up to 2000 W.

Components

A simplified gas piping diagram of the refuelling station is shown in Fig. 3.

The one-stage MH compressor (1) comprises of two compression modules (Module 1, Module 2) each of which includes three MH containers (1.1.1...1.1.3 and 1.2.1...1.2.3) connected in parallel to gas manifolds, pressure sensors (1.3...1.6), manual shut-off valves (H₂ input, 1.7; H₂ output, 1.17), check valves (1.8, 1.9, 1.14, 1.15), remotely controlled pneumatically actuated shut-off valves (1.10...1.13, 1.16), safety relief valve (1.18), H₂ coolers (1.19, 1.20).

The H₂ dispenser (2) is connected to the output of the compressor in parallel to the gas buffer (3). The main parts of the dispenser (2) include remotely controlled pneumatically

Fig. 1 – General layout of the hydrogen refuelling station.

Fig. 2 – Images of the hydrogen refuelling station including connections of service pipelines (right). Labelling of the components corresponds to Fig. 1.

actuated shut-off valves (2.1...2.3), check valves (2.4, 2.5), H₂ mass flow meter (2.6), pressure sensor (2.7), remotely controlled pressure regulator (2.8). The dispenser is also connected to the H₂ supply and vent pipelines of the refuelling nozzle (5a) and H₂ venting pipeline (6).

The control block (4) provides periodic heating and cooling of the compression modules (1.1, 1.2), as well as switching gas flows during operation of the MH compressor by the opening/closing the valves 1.10...1.13, 1.16. It also provides operation of

the dispenser (2) by the opening/closing the valves 2.1...2.3 and setting the pressure regulator 2.8.

More detailed description of the components is given below.

MH compressor

For the H₂ compression, we used a C14-AB₂-type Ti_{0.65}-Zr_{0.35}(Mn,Cr,Fe,Ni)_{2+x} hydride forming alloy. As it can be seen from Fig. 4, this material allows H₂ compression from P_L = 50 bar to P_H = 200 bar in the temperature range 25–130 °C with a cycle productivity about 100 NL H₂/kg.

More details about characterisation of the used MH material are presented in Ref. [9] and [14] (sample #5).

The material was loaded in six MH containers for H₂ compression.

The MH container is made of stainless steel (seamless pipe ASTM A312 GR.TP 316 SHED 80S for the pressure vessel body) and has the following features:

- Water cooling to T_L–15–20 °C;
- Direct steam heating to T_H–120–140 °C;
- Internal “tube in tube” heat exchanger (stainless steel core tube with extruded aluminium fins);
- External heating/cooling jacket.

Each container (ø101.6 × 1619 mm, void volume 4.755 L, design pressure/temperature 200 bar/–50...+200 °C) was loaded with 14.6 kg of MH material including 13 kg of the AB₂-

Fig. 3 – Simplified gas piping diagram of the refuelling station. Numbering of the main components (1–6) corresponds to Fig. 1 and 2. To illustrate the operation of the MH compressor, the closed valves are shown as filled and the opened ones as empty.

Fig. 4 – Pressure – composition isotherms for H₂ absorption at the low temperature (T_L) and H₂ desorption at the high temperature (T_H) for the AB₂-type MH material used in the H₂ compressor.

type alloy described above mixed with 1.45 kg of AB₅-type hydrogen storage alloy (La_{0.8}Ce_{0.2}Ni₅) and 0.15 kg of expanded natural graphite (ENG) powder. According to our solution [15], the additives were used for facilitation of the activation (AB₅) as well as for the improvement of heat transfer in the MH bed, in combination with minimizing stresses on the container's

wall due to swelling of the bed¹ in the course of hydrogenation (ENG).

More details about design of the MH container and its performances during H₂ compression are presented in Ref. [9].

The MH compressor maintains high hydrogen pressure (195–200 bar) in the buffer storage cylinder pack (3 in Figs. 1–3) by the compression of low pressure (50–60 bar) hydrogen supplied from the input pipeline (H₂ In in Fig. 3). The H₂ compression is thermally driven and does not consume electric power. It is provided by the periodic (i) cooling of MH material in MH containers assembled in two compression modules accompanied by low pressure hydrogen absorption therein and (ii) heating of the MH material in the MH containers accompanied by high pressure hydrogen desorption therefrom.

The main gas piping elements of MH compressor include (Figs. 3 and 5):

- Hydrogen input pipeline (H₂ In);
- Hydrogen input (1.7) and output (1.17) manual valves equipped with position sensors;
- Pressure sensors installed at hydrogen input (1.3), gas manifolds of the containers (1.4, 1.5), and hydrogen output (1.6);

¹ Filling density ~55% of the material's real density in the hydrogenated state.

Fig. 5 – Views of the gas piping of the MH compressor. Labelling of the components corresponds to Fig. 3.

- Arrangement of pneumatically actuated (1.10...1.13) and check (1.8, 1.9, 1.14, 1.15) valves periodically switching hydrogen flows between gas manifolds of the compression modules and input/output H₂ pipelines;
- Six MH containers (1.1.1...1.1.3 and 1.2.1...1.2.3) equipped with 0.5 μm sintered metal inline filters and manual shut-off valves (see Fig. 5, left);
- Fine inline filters (F1, F2; 0.003 μm) installed between gas manifolds of the compression modules and other gas systems of the compressor;
- Coolers (1.19, 1.20) for lowering temperature of the high pressure hydrogen delivered from the heated MH containers;
- Safety relief valve (1.18; set cracking pressure 210 bar);
- Pneumatically actuated valve (1.16), for the connection to vent pipeline (6) when regeneration of the MH material is necessary;
- Manual valves (not shown) for purging the gas systems with nitrogen (for installation and service works only).

The cooling of the MH containers/compression modules is provided by running water, and the heating – by steam. Fig. 6 shows the steam and water piping diagram in the heating/cooling system.

The steam and water piping elements of the MH compressor include:

- Heating/cooling circuits of Module 1 and Module 2 formed by the parallel connection of the heat exchangers of MH containers. Each MH container has an internal heat exchanger and an external heating/cooling jacket connected in sequence. The internal heat exchangers are connected to steam/water manifolds at the top of the module/container's assembly (TMF1, TMF2) while the external heating/cooling jackets – to the manifolds (BMF1, BMF2) at the bottom. The opposite direction of the heating (steam) and cooling (water) fluids results in faster system response when switching from cooling to heating and vice versa.
- Connecting pipelines for the supply (Water supply) and return (Water out) of the cooling water.
- Connecting pipelines for the Steam supply and Condensate drain.
- Pneumatically actuated valves for water supply to Module 1 (PV1) and Module 2 (PV2).
- Pneumatically actuated valves for water drain from Module 1 (PV3) and Module 2 (PV4).
- Heat exchangers of the coolers of hydrogen delivered from Module 1 (HE1) and Module 2 (HE2).
- Pneumatically actuated valves for steam supply to Module 1 (PV5) and Module 2 (PV6).
- Pneumatically actuated valves for condensate removal from Module 1 (PV7) and Module 2 (PV8).

Fig. 6 – Steam and water piping diagram of the MH compressor. The closed valves are shown as filled and the opened ones – as empty.

- Top (T1) and bottom (T2) temperature sensors of Module 1 heating/cooling circuit.
- Top (T3) and bottom (T4) temperature sensors of Module 2 heating/cooling circuit.
- Steam trap (ST1) with pneumatically actuated bypass valve (PV9).

The operation of the compressor is provided by the control block by opening and closing gas (1.10...1.13, 1.16) and steam/water (PV1...PV9) valves thus providing one of the operation modes listed in Table 1. The compressor is automatically switched from the H₂ compression to the standby mode when the output pressure exceeds 200 bar. In doing so, both modules are cooled down to be charged with H₂. The H₂ compression mode is activated again when the output pressure drops below 195 bar.

The regeneration mode provides recovery of hydrogen sorption performance of the material by a long heating-up the MH containers with simultaneous release of hydrogen and residual gases into venting line. The regeneration is followed by the charge of the cooled MH containers with H₂, similar to the standby mode.

Dispenser

The dispenser (Figs. 3 and 7) provides H₂ supply to the refuelling nozzle connected to the forklift hydrogen receptacle

and venting of the pressurised hydrogen after completion of the refuelling.

The main elements of the dispenser include:

- High pressure hydrogen supply valve (2.1);
- Hydrogen output valve (2.2);
- Hydrogen venting valve (2.3);
- Hydrogen venting check valves (2.4, 2.5);
- Flow meter (2.6);
- Dispensing pressure sensor (2.7);
- Electro-pneumatically actuated pressure regulator (2.8).

After connection of the refuelling nozzle to hydrogen receptacle of the forklift fuel cell power module and sending the command by the operator from the control block, the dispenser provides safe filling of the forklift hydrogen storage system with the pressurised hydrogen. The filling stages (see Fig. 8) include:

- Delay of the beginning of pressure increase after sending the command to start refuelling (Start Delay, 0.5–1 min);
- Smooth increase of H₂ dispensing pressure setpoint to the maximum value of (185 bar) during Ramp Time, 5–15 min;
- Maintaining of the maximum H₂ dispensing pressure during Settling Time, 5–10 min;

Table 1 – Modes of operation of the MH compressor.

Mode	Operation	Duration	Positions of valves (O – opened, C – closed)													
			Gas (Fig. 3)							Steam/water (Fig. 6)						
			1.10	1.11	1.12	1.13	1.16	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8	PV9
Hydrogen compression ^a	1. H ₂ suction in Module 1/H ₂ discharge from Module 2 (preheat)	5–6 min	O	C	C	O	C	O	C	O	C	C	O	C	O	O
	2. H ₂ suction in Module 2/H ₂ discharge from Module 1	15–25 min	O	C	C	O	C	O	C	O	C	C	O	C	O	C
	3. H ₂ suction in Module 2/H ₂ discharge from Module 1 (preheat)	5–6 min	C	O	O	C	C	C	O	C	O	O	C	O	C	O
Standby	4. H ₂ suction in Module 2/H ₂ discharge from Module 1	15–25 min ^b	C	O	C	C	C	C	O	C	O	O	C	O	C	C
	H ₂ suction in both modules (cooled)		O	O	C	C	C	O	O	O	O	C	C	C	C	C
	1. H ₂ release from both modules (heated)	5–8 h	C	C	O	O	O	C	C	C	C	O	O	O	O	C
Regeneration	2. H ₂ suction in both modules (cooled)	2 h	O	O	C	C	C	O	O	O	O	C	C	C	C	C

Notes:

^a – periodic.^b – depends on the output pressure (see above). **Fig. 7 – View of the dispenser section. Labelling of the components corresponds to Fig. 3.** **Fig. 8 – Operation cyclogram of the hydrogen dispenser.**

- Smooth decrease of H₂ dispensing pressure from the maximum value to zero during *Depressurizing Time*, 3–5 min.

Due to relatively slow pressure ramping, 5–15 min, hydrogen supplied to the storage system on-board the forklift is not overheated: maximum temperature of ~55 °C was observed in the MH extension tank during the first 5–8 min of the refuelling cycle [13]. This eliminates requirement for deep cooling of the dispensed H₂ thus resulting in a simpler design and lower costs of the developed refuelling station.

Buffer

The necessary amount of the compressed H₂ is provided by the buffer storage (3 in Figs. 1 and 2), a standard pack frame assembly of 18 gas cylinders (supplier Air Products South Africa (Pty) Ltd), with the total internal volume of 900 L and hydrogen storage pressure up to 200 bar. The buffer is connected to both hydrogen dispenser and MH hydrogen compressor; the latter maintains the maximum H₂ pressure (195–200 bar) in the buffer during the operation of the hydrogen refuelling station.

Fig. 9 – Parts of the refuelling console.

Refuelling console

The refuelling console (5 in Fig. 2) carries the elements necessary for the safe forklift refuelling. These elements are shown in Fig. 9.

The refuelling of the forklift is provided by the TK-16H2 refuelling nozzle (1; maximum dispensing pressure 250 bar) to be connected to hydrogen receptacle of the forklift fuel cell power module (see Fig. 9, right). The nozzle is equipped with two flexible hoses (2), one for H₂ supply and another for the safe H₂ vent when disconnecting the nozzle from the receptacle. Both hoses are connected to TSA-1 H₂ breakaway coupling (3) installed on the console to avoid abrupt release of high pressure hydrogen if the forklift will accidentally move during the refuelling. The parts 1–3 were supplied by WEH GmbH, Germany. Further connection of the hydrogen supply and venting lines to hydrogen dispenser is provided by 3/8" OD 316 stainless steel pipelines.

As a rule, the refuelling has to be accompanied by the removal of water formed during the operation of the forklift fuel cell power module. To perform this operation, the system is equipped with a flexible hose for water removal (4) with a quick coupling which, when water tank of the forklift power module has to be emptied, is connected to the dewatering nipple of the forklift power module. From the other side, the hose (4) is connected to the ejector (5). The ejector (5) is also connected to the compressed air line, via manual shut-off valve (6); the water is drained to pipeline (7).

To avoid appearance of electric sparks, the console also has an earth clamp (8) which is connected to a metal part of the forklift before the refuelling.

Control block

The control block (4 in Figs. 1 and 2) provides fully automated operation of the refuelling system with minimal interventions from the operator via human machine interface (HMI) using Siemens programmable logic controller (PLC).

The control block is assembled in a frame (Fig. 10 left) and is connected to (i) electric supply cable, (ii) source of compressed air, (iii) electric and (iv) pneumatic systems of hydrogen dispenser and compressor unit. Depending on the available electric supply, the control block can be powered

from industrial (525 V) or common (230 V) single-phase AC network (10 A, 50 Hz); the corresponding change-over switch is located inside the compartment. Electric cable connecting the block with the hydrogen dispenser and compressor unit provides the powering (24 VDC) of sensors located in the latter and receives the corresponding sensor signals via Ex-proof barriers while the actuation of valves and pressure controller is provided by pneumatic pipelines.

Switching the system on is provided by an isolator switch located on the top left of the block compartment (1; Fig. 10 (left)). All other controls and indicators are located in the front door, including emergency stops of the whole system (2) and the dispenser (3), HMI touch-screen (4), and panel switches, indicators and ports (5); see also Fig. 10 (right). The control panel elements include: *Compressor Off/On* selector switch; *Compressor Active* indicator; *Alarm Active* indicator; *Start H2 Filling* push button; *H2 Filling Busy* indicator; *H2 Filling Complete* indicator; *USB Data Logging* port; and *Ethernet* port.

The control block provides:

- Fully automated operation of the MH compressor (see Table 1) including switching between operation and standby modes, when the selector switch *Compressor Off/On* is on;
- H₂ refuelling independent on the operation of the MH compressor, after pushing *Start H2 Filling* button;
- Visual monitoring, data logging and control of system parameters including switching the compressor to regeneration mode and manual operation of all system components, via HMI interface;
- Change of the operation setpoints via HMI interface including:
 - Duration of stages for the different modes of the operation of MH compressor (Table 1);
 - Maximum dispensing pressure and duration of stages for H₂ refuelling (Fig. 8);
 - High and low pressure limits for the switching between the operation and standby modes;
 - Other system parameters including pressure differences when opening valves 1.10...1.13 (Fig. 3), as well as alarm setpoints.

Fig. 10 – Front view of the control block (left) and panel door layout (right).

Fig. 11 – Site layout (top view).

Fig. 12 – Site layout (side view).

Fig. 13 – Typical operation of the hydrogen refuelling station. For the clarity, pressures and temperatures for the second compression module (M2) are not plotted on the right graph. The plots showing the temperatures of the compression modules are shown by solid and dashed lines for the top and bottom steam/water manifolds, respectively.

Safety

Although the refuelling station is an experimental prototype, it complies with South African safety regulations for the operation in fire-and-explosion hazardous environment [16,17]. For the determination of the hazardous zones, we also used the results of analysis of the relevant EU directives [18].

The zone classifications and sizes (Figs. 1, 11 and 12) can be considered as conservative due to the following factors:

- The station is an open air installation, and the wind speed of 0.5 m/s is conservative.
- Hydrogen gas is 14.5 times lighter than air and thus has a high buoyancy. The released H_2 will rise immediately, and the shape of the hazardous zone will rather form an upward plume than a sphere.
- The station was checked by professionals using hydrogen detecting devices before the plant was put into operation;

the H_2 leak tests are carried out periodically (every 3 months), as well as after each service work.

- The station is located in a locked environment with access control. The operating personnel is experienced with hydrogen gas and its related risks.

All electric parts used in the equipment located in the hazardous zone (H_2 compression and dispensing unit) are Ex-proof rated and additionally certified by South African safety authorities.

On-site operation

Details

The refuelling station was commissioned at Impala Platinum Refineries in September 2015 and officially launched in March 2016.

Fig. 14 – Typical daily operation of the refuelling station showing pressures (P) and temperatures (T) in the compression modules (M1, M2; the temperatures are plotted for the top manifolds), the pressures in the buffer and the output of the dispenser during refuelling (see inset), as well as the ambient temperature (RT).

Figs. 13 and 14 illustrate typical on-site operation of the station.

As it can be seen from Fig. 13, after beginning of the heating of a compression module, the temperatures in the top (steam inlet) and the bottom (condensate drain) manifolds equalise ($T = 100\text{ }^{\circ}\text{C}$) in 5–6 min then gradually approaching $\sim 140\text{ }^{\circ}\text{C}$ by the end of the heating cycle (20 min). The heating results in a fast (130 bar in ~ 4 min) increase of the H_2 pressure in the gas manifold of the compression module; when the module pressure exceeds the pressure in the buffer at the output of the compressor, the compression module discharges high

pressure H_2 into the buffer. Since the modules M1 and M2 are working in the opposite phases, the buffer pressure continuously increases, with short (~ 5 min) interruptions in the periods between the end of heating of module M1 (M2) and beginning of heating of the opposite module M2 (M1).

After switching into the cooling mode, the temperatures of the bottom (water input) and top (water output) manifolds start to decrease immediately. The temperature at the input drops to its inlet value ($15\text{--}30\text{ }^{\circ}\text{C}$ depending on the season and time) in ~ 7 min while water temperature at the output of the module decreases more slowly, with the difference

Fig. 15 – Operation of the MH compressor during the first (left; November 2015) and the third (right; December 2018) years of operation.

($T_{\text{output}} - T_{\text{input}}$) decreasing to 3–5 °C by the end of the cooling cycle (20 min). Nevertheless, the pressure in the cooled module quickly drops approaching H_2 inlet pressure in 4–5 min when T_{output} decreases to ~60 °C.

After the buffer pressure reaches 200 bar, the compressor is switched from the operation to the standby mode. In doing so, both modules are cooled down and all MH containers become almost completely charged with hydrogen. Due to that, when the operation of the compressor is activated again, the H_2 compression productivity at the beginning is higher, and restoring the buffer pressure to $P = 200$ bar requires less than one full compression cycle when the buffer pressure decrease was caused by the decrease of the ambient temperature, or 2–4 full cycles after the refuelling (Fig. 14).

Fig. 15 (left) illustrates the operation of the MH compressor (time dependencies of the buffer pressure and amount of H_2 in the buffer calculated using real gas equation) at the beginning of the operation (November 2015). Linear fit of the time dependence of the H_2 amount in the buffer allowed to calculate the average compressor productivity to be of 13.5 Nm^3/h (28 kg H_2/day). Similar measurements taken after 36 months of the operation of the compressor (Fig. 15 (right)) showed about two-times drop in the productivity (to 6.8 Nm^3/h or 14.5 kg/day). It has to be noted that the pronounced drop of the productivity took place during the first 6 months of the operation, and thereafter the productivity was quite stable mostly varying between 5.5 and 7.2 Nm^3/h .

The observed drop in the productivity of the MH compressor may have several origins including:

- i. Degradation of the crystal structure of the intermetallic caused by the cycling and resulting in the drop of the reversible hydrogen storage capacity of the material at the operating conditions.
- ii. Deterioration of hydrogen absorption/desorption kinetics caused by trace impurities of oxygen and water vapours in the feeding H_2 which may be accumulated in the gas systems of the compressor.
- iii. Malfunctions of the system components during prolonged operation.

We note that as distinct from the AB_5 -type alloys whose degradation behaviour during prolonged cycling is well studied (see, e.g. Ref. [10] and references therein), only several studies on cycling stability of the AB_2 -type intermetallics were published so far [19–27]. The recent studies [23–27] were mainly focused on the surface passivation effects in AB_2 -type hydrogen storage materials mainly related to their electrochemical applications [25–27], and only few works deal with cycling stability of the AB_2 -type MH materials in gas phase applications.

It was shown [21] that extended thermal cycling of C14- AB_2 intermetallic in H_2 (>85 000 cycles in the temperature range 45–120 °C) results in insignificant change of the PCT behaviour of the hydrogen storage material, and the loss of the reversible hydrogen storage capacity is below 10%. The cycling does not result in a significant change of phase composition of the material except for the appearance of trace amount of a

new phase identified in Ref. [21] as Zr and broadening XRD peaks of the AB_2 phase; the latter effect was also observed in Ref. [22]. Thus a contribution of degradation of the AB_2 -type material (factor i) in the drop of the MH compression productivity seems to be unlikely.

According to the information from Impala Platinum who consumes hydrogen which also feeds the MH compressor, its purity is above 99.99% with negligible concentration of critical impurities (CO and CO_2 less than 1 ppm each, no sulphur). However, trace amounts of other impurities, first of all water vapours, may present in the feeding H_2 . As known from the literature [23,24,28], the presence of water vapours in H_2 may deteriorate hydrogen sorption performance of AB_2 in a some extent. However, hydrogen sorption performance of the passivated material can be recovered by applying the regeneration procedure described above.

Indeed, the permanent operation of the compressor during every 5–6 months in 2017–2018 resulted in a gradual decrease of the productivity from 6.5–7.2 to 5.5–6.2 Nm^3/h (~15%), and after carrying out the regeneration, the productivity was completely restored. It allows us to conclude that the passivation of the MH material by the impurities in the feeding H_2 (factor ii) contributes in the observed two-fold drop of the productivity only partially.

Apart from gradual decrease of the compressor's productivity mentioned above, two system malfunctions identified during the operation of the refuelling station resulted in a significant, down to 3 Nm^3/h , drop of the productivity of the H_2 compressor. These malfunctions included:

- Contamination of the pipelines with very fine powder of the MH material that resulted in H_2 backflow through check valves 1.8, 1.9, 1.14, 1.15 (Fig. 3).² The issue has been resolved by the installation of fine inline filters (F1, F2 in Fig. 3) in addition to 0.5 μm grade filters attached to the MH containers;
- Malfunctions of the control system due to: (i) failures of electric components and (ii) errors of pressure sensors (1.4, 1.5 in Fig. 3) used for a feedback in the control of gas valves.

After fixing the above-mentioned failures in May 2017, the productivity of the compressor remained in the range 5.5–7.2 Nm^3 without further drop, when the regeneration was carried out every 5–6 months.

Taking into account the above-mentioned, we believe that the major loss of the productivity was caused by malfunctions of the system components (factor iii). Most probably, the main origin was in a blocking of the 0.5 μm grade sintered metal filters attached to the MH containers by a fine MH powder; the blocking could not be completely eliminated by the “back-wash” with H_2 during its absorption.

Certainly, the origin of the observed deterioration has to be investigated in more details; the corresponding studies related to both material and engineering issues are underway.

² Initially, the pneumatically actuated valves 1.10–1.13 were not installed; added at the later stage.

Table 2 – Summary of the operation of the hydrogen refuelling station (September 2015–January 2019).

Parameter	Value	
	Module 1	Module 2
Operating hours of H ₂ compressor*	2410	1562
Operating cycles	5042	4557
Regeneration hours	20	
Standby hours	8241	
Service hours	40	
Amount of H ₂ compressed [Nm ³]	1173	
Amount of H ₂ dispensed [Nm ³]	750	
Operation days logged	530	

Note: * – during the time when T > 60 °C.

Summary

Main parameters of the hydrogen refuelling station during its 38 month long on-site operation since commissioning in end September 2015 are summarised in Table 2.

It can be seen that during the logged period (530 full days), the refuelling station was mostly in the standby mode because of servicing only one fuel cell forklift which was used not very intensively and required refuelling only 1–2 times a week. Due to that, the decrease of the compressor productivity described above was not critical for the customer.

It also can be seen that the operation time of Module 1 of the compressor was ~50% longer than for the Module 2. It is explained by the operation algorithm when the switching of the compressor from the standby back to the operation mode starts from the heating of Module 1. In the future, the algorithm will be modified to allow more uniform workload distribution between the compression modules. Finally, the difference between amounts of the compressed and dispensed hydrogen has its origin in H₂ venting from the buffer during the service works.

Despite some issues mentioned above, the prolonged operation has shown the feasibility of application of MH H₂ compression technology in medium-pressure (up to 200 bar) refuelling of the fuel cell forklifts. The ways to further optimise the system performance towards increase of reliability, productivity and efficiency include (i) identifying the origin of

the decrease of the productivity during prolonged operation and minimizing this effect by the corresponding material and engineering solutions; (ii) further improvement of the design of the MH container and its accessories, to reduce heat losses during its thermal cycling and to eliminate contamination of the released H₂ with fine MH powder; (iii) further optimisation of heating/cooling circuits in the system with possible introduction of the heat recovery option [29]; (iv) further optimisation of the operation parameters including the algorithms of switching between the standby and operation modes, process setpoints, etc.

Economic estimations

Fig. 16 presents breakdown of the direct costs (without labour) incurred by HySA Systems for the making and installation of the hydrogen refuelling station. The total costs accounted 1.94 million South African Rand that was equivalent to USD ~140 thousand (the rate on September 30, 2015 [30]).

The main part of the costs (28%) relates to the design, making and assembling of the parts of the refuelling station. 25% of the total costs were spent for the making main components of the MH compressor including MH material (~¼) and MH containers (the balance).

The annual operation costs of the refuelling station were estimated as 100 thousand South African Rand (about USD 7 thousand; the rate for December 2017). We note that these costs mainly incurred for the service and upgrade of the prototype to eliminate its defects which can be identified only during prolonged operation, will be significantly lower in the future when the defects will be eliminated already at the design stage.

As it can be seen, even for the prototype, both capital and operation costs are significantly lower than for the standard 350–700 bar hydrogen refuelling stations available on the market (see Introduction). These benefits are due to: (i) lower H₂ dispensing pressure which enables the use of standard gas service components; (ii) slow pressure ramping which prevents overheating of the supplied H₂ and, thus, eliminates the requirement for deep cooling; (iii) the replacement of a mechanical H₂ compressor with the MH one.

Fig. 16 – Breakdown of the incurred costs (in South African Rand, 2015) for the making and installation of the hydrogen refuelling station.

Conclusions

In this work, we reported about features and experience of 38 month-long uninterrupted operation in the industrial environment of a prototype medium-pressure (dispensing at 185 bar) hydrogen refuelling station with integrated 50–200 bar metal hydride hydrogen compressor which utilises services available at the customer's site.

The station is characterised by simplicity in design, operation and service, high safety and reliability, noiseless operation, and lower capital and operating costs than high-pressure (350–700 bar) hydrogen refuelling stations available on the market.

Despite a number of issues mainly resulting in the decrease of the productivity of the metal hydride compressor, the on-site operation has shown the feasibility of application of the metal hydride hydrogen compression technology in the medium-pressure refuelling of fuel cell forklifts. We have demonstrated several ways to further optimise the system performance towards increase of reliability, productivity and efficiency.

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