IMPLEMENTATION OF A DOUBLE-SHELL METAL HYDRIDE TANK INTO REAL BUS OPERATION AND ITS TEST RUNS

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Recently, the role of hydrogen technology has become more important in decarbonizing society and achieving carbon neutrality goals. The most important sector where it is possible to implement hydrogen technologies to achieve carbon neutrality is the automotive industry. For hydrogen technologies in the field of transport to be able to compete with conventional motor vehicles, research in several areas is necessary. One of the most important areas is the issue of hydrogen storage. The article in question discusses the issue of low-pressure hydrogen storage by means of metal hydride storage tanks for mobile applications and solves the design of a double-shell metal hydride storage tank using an active and passive cooling module and the subsequent implementation of the metal hydride storage tank in the real operation of a bus on which test runs were carried out and evaluated. From the test runs, it was found that research and development in the field of initial preheating of the metal hydride storage tanks in the bus is necessary for the efficient removal of hydrogen into the fuel cell.

KEYWORDS

Hydrogen, carbon neutrality, metal hydride, storage, decarbonization

1 INTRODUCTION

In post-fossil energy systems, hydrogen can gain crucial role as a secondary energy carrier, especially for transportation purposes. This widely published claim is justified by the fact that hydrogen can be produced from electricity provided by, for example, wind turbines or photovoltaic systems. The hydrogen supply depends on the availability of electricity and is then stored for use depending on the given need. However, efficient storage of hydrogen as an energy carrier is difficult from a technical and economic perspective, for example due to the fact of low volumetric energy density of hydrogen under standard conditions, as well as other demanding properties. Especially for mobile applications (e.g. cars, trucks, ships, trains) it is very important to have hydrogen storage options with high volumetric and gravimetric energy density to enable highly efficient use of hydrogen and to be fully competitive with other options in the transport sector [Lototskyy 2017], [Yang 2017]. Various storage technologies and concepts have therefore been developed in recent years to achieve this challenging goal. The most common way of storing hydrogen is through compressed hydrogen gas, which is most common in commercially sold systems, for example in personal cars such as the Toyota Mirai, where the working pressure of the tanks is at the level of 70 MPa, and for buses the maximum pressure is reduced to 35 MPa. Due to the extremely high working pressures in the tanks, this method is considered not the safest.

Another and promising method of hydrogen storage is low-pressure storage through metal hydride compounds, which consist of a host crystal lattice of a metal and hydrogen atoms are in the interatomic space of the crystal lattice of the metal. The working pressures of metal hydride tanks are at the level of 1-2.5 MPa, which provides room for increasing the safety and storage of hydrogen in mobile applications [Klopčič 2023].

However, there are also disadvantages that make further research and innovation in this area necessary. The gravimetric energy density is very low, which leads to the high mass of the metal hydride tanks. Also, during the process of hydrogen absorption into the interatomic space of the metal, heat is released. For example, with an alloy based on LaCeNi, for 1 m^3 of stored hydrogen, up to 1 MJ of heat is released [Jasminská 2015]. For this reason, it is necessary to create an efficient way of cooling the tanks.

The mentioned shortcoming needs to be solved by cooling the metal hydride alloy during the refueling process, which can be solved by means of active, passive modules or their combination. One method is the use of active tube cooling, which is used in commercially available HBond®9000 tanks, which are located directly in the metal hydride alloy tank. The disadvantage of this system is the occurrence of high-pressure losses in the tank during refueling of hydrogen into the interatomic space of the metal, thereby storing a smaller amount of hydrogen in the metal hydride alloy [Tóth 2018]. Wang et al. studied a tank filled with a metal hydride alloy based on $LaNi_5$ with an embedded spiral cooling tube, which acted as an active cooling module embedded in the metal hydride tank [Wang 2012]. This system significantly reduced pressure losses and is therefore considered one of the suitable proposals for mobile applications.

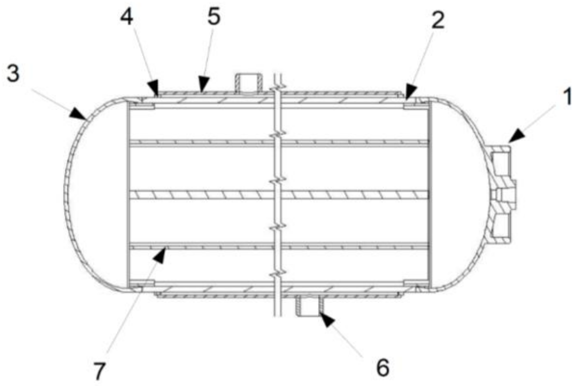
Another option for efficient heat removal from the core of the metal hydride storage tank during the process of hydrogen absorption into the metal alloy structure is the use of passive cooling modules in the form of internal heat transfer intensifiers integrated directly into the metal hydride storage tanks, made of material with high thermal conductivity, for example aluminium [Macdonald 2006], [Tóth 2023]. The advantage of this system is that there are almost no pressure losses in the tank, but it is necessary to cool the removed heat with an active cooling module, which is located on the outside of the tank with a metal hydride alloy.

In this article, a double-shell metal hydride storage system is analysed in detail, which consists of an active and a passive cooling module, and the subsequent implementation of the designed storage tank in real bus operation.

2 CONSTRUCTION DESIGN OF A METAL HYDRIDE TANK

When designing the storage tank, it was necessary to base it on the European standard STN EN 13322-2. It is a standard that specifies the specification for transport cylinders for gases, their design and the production of refillable steel tanks. [Brodnan 2006]. The design of the solved storage tank consists of two main parts, namely the primary tank, in which there is a hydrogen-absorbing metal hydride alloy, and the casing shown in Figure 1. Between the primary tank and the casing, there is an intermediate space in which the cooling liquid flows. Stainless steel type 1.4404 or 316L was chosen for the construction of the metal hydride tank. The chosen steel is compatible for hydrogen applications based on the mentioned standard.

As part of the design of the metal hydride tank, the commercially available metal hydride alloy Hydralloy C5 of AMG Titanium GfE, whose composition is based on MnTiVFeZr, is being considered.



1- cylindrical part of the primary tank 2- elliptical bottom with hole and flange NPT1/4", 3- elliptical bottom, 4- flange for casing, 5- the cylindrical part of the casing, 6- flange G1/2, which serves as the coolant supply, 7- flange G1/2, which serves as a coolant outlet, 8- heat transfer intensifier

Figure 1. Design of a metal hydride tank

The active cooling module in the designed tank is represented by the cooling liquid, which is located in the intermediate space between the primary tank and the casing. The passive cooling module is located inside the primary storage tank and represents the so-called heat transfer intensifier. This intensifier serves to increase heat removal from the core of the tank in the direction of the intensifier's fins to the wall of the primary tank, where the tank is cooled by the cooling liquid. By changing the geometry of the intensifier, it is possible to improve heat dissipation, thereby improving the absorption process. When designing the heat transfer intensifier, aluminium is considered because it has good thermal conductivity ($237\ W \cdot m^{-1} \cdot K^{-1}$).

The basic characteristics of the designed tank are shown in the Table 1.

Weight of empty container (kg)	Weight of metal hydride in the tank (kg)	Weight of container with metal hydride (kg)	Amount of hydrogen (kg)
27,93	46,07	76	0,762

Table 1. Basic parameters of the designed metalhydride tank

Subsequently, the tank is designed and analysed by strength calculations and the necessary tests, which are specified in the standard STN EN 13322-2.

On the basis of strength simulations, it was found that the designed tank complies with the operating parameters, as the tension created at a working pressure of 3 MPa was approximately 100 MPa. With a test hydraulic pressure of 4.7 MPa determined from the mentioned standard, it was approximately 143.6 MPa and did not exceed a value higher than the yield strength of the selected material determined by the manufacturer, which was 210 MPa.

3 MEASURING THE OPERATIONAL PARAMETERS OF THE DESIGNED MNTZV159 TANK IN A BUS

The designed double-shell storage tank with an internal heat transfer intensifier according to the STN EN 13322-2 standard was subsequently used in the bus concept in cooperation with Rosero s.r.o., using metal hydride alloys and a fuel cell for its propulsion. Within the system there are 6 metal hydride tanks, which are located on the underside of the chassis as shown in Figure 2.

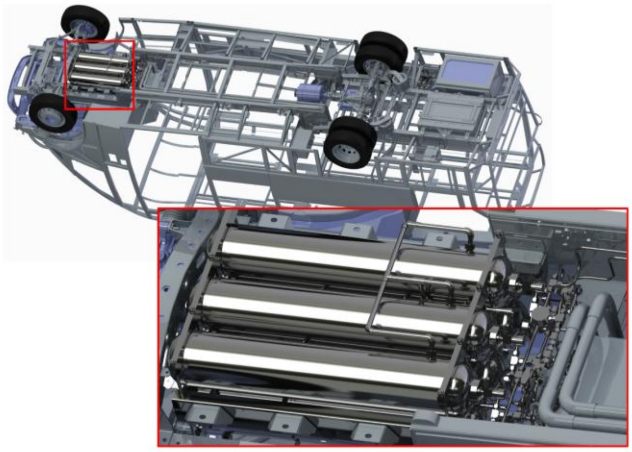


Figure 2. The location of the metal hydride storage tanks of the first bus design

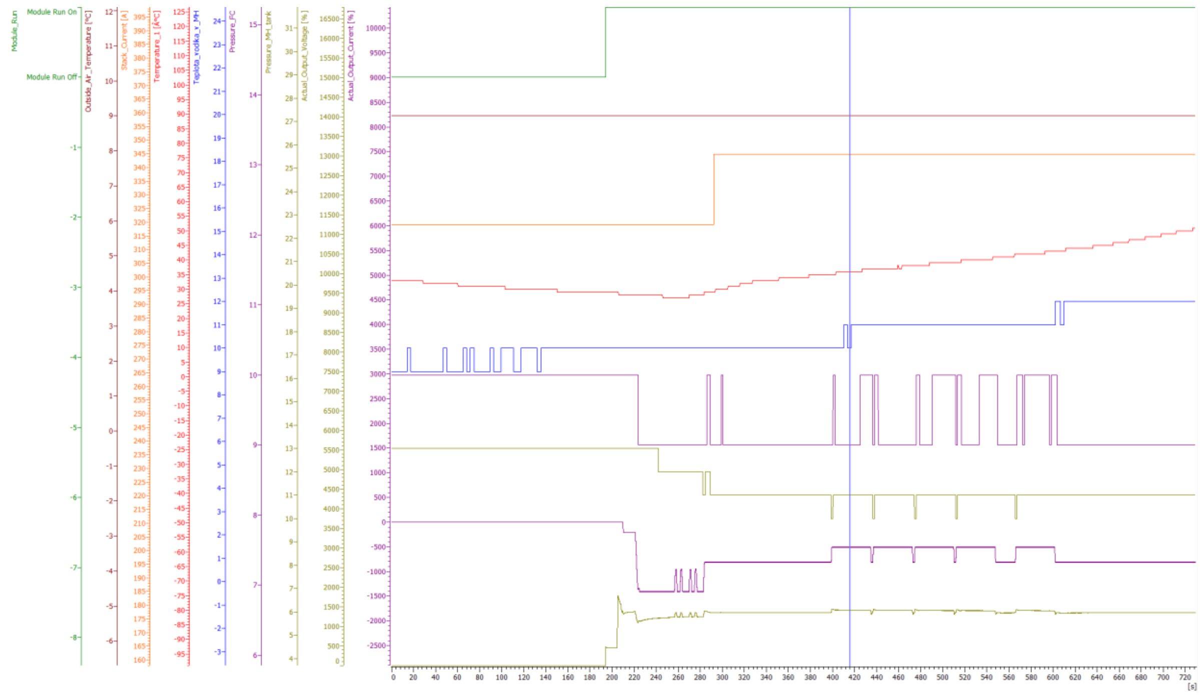
The device is a hybrid that is powered by electricity generated in a fuel cell. A fuel cell is an electrochemical device that converts the chemical energy of the fuel and oxidizer directly into electrical energy. A fuel cell with a proton exchange membrane (PEM) from Ballard FCveloCity®-MD30 Fuel Cell Module with a nominal power of 30 kW was used for the design of the mobile device.

Subsequently, test runs of the designed bus were carried out, where parameters such as pressure, current, voltage on the fuel cell, temperature of hydrogen and tank pressure were determined, and then the mass flow of hydrogen from the tanks and the power of the selected fuel cell were evaluated. The tanks were filled to about 2/3 of their maximum capacity. The first test drive was carried out on August 24, 2022. The outside temperature during the measurement was 23 °C.

Based on the first measurement from 24.08.2022, it was found that the heat generated from the fuel cell was not enough for the initial preheating of the tanks, which resulted in insufficient desorption of hydrogen from the structure of the metal alloy and thus low mass flow of hydrogen and low pressure on the fuel cell, which corresponded to a value of 8 bar. It could not be started for that particular reason.

To solve the problem, the heating system of the metal hydride tanks must be optimized in order to optimally release hydrogen from the MH alloy.

The initial preheating of the metal hydride storage tanks in the bus was carried out by a high-voltage heater from the traction battery with a power of 5 kW, which plays an important role in heating the metal hydride storage tanks, especially during the winter season.



Where: the green curve represents the switching on and off of the fuel cell module (-), the brown curve represents the outside air temperature (°C), the yellow curve represents the balancing current on the fuel cell (A), the red curve represents the temperature of the liquid needed to heat the tanks (°C), the blue curve represents the temperature of the hydrogen entering the fuel cell (°C), the light purple curve represents the pressure in the fuel cell (Pa), the light green curve represents the pressure in the tank (Pa), the dark purple curve represents the instantaneous current on the fuel cell (A), the light-green curve that is at the very bottom of the graph represents the instantaneous voltage on the fuel cell (V).

Figure 3. Second measurement from March 8, 2023

The last measurement on the bus was carried out in the winter of March 8, 2023, where the system also included a high-voltage heater from a traction battery, which enabled preheating of the storage tanks. The outside temperature at the first measurement was 9 °C. After approximately 25 minutes since the start of the system, the heaters have heated the tanks to a temperature of approximately 45 °C and the pressure of the tanks was at the level of 13 bar.

Figure 3 shows the second measurement during the test drive from 8.3.2023, where the fuel cell ignited at 200 s. At the time of 260 s, the temperature of the water at the inlet to the storage tank began to rise through the waste heat generated from the fuel cell. At 260 s, there was also a pressure drop on the tanks, due to the initial run-up of the fuel cell.

During the third measurement on March 8, 2023, the system was shut down and turned off, where it is possible to see how after the fuel cell is turned off, the pressure of the tank increases back to the initial value of 13 bar.

Based on the current and voltage curves, it was possible to plot the power curve of the selected fuel cell through the following relationship.

$$P_{el} = U \cdot I \qquad \text{(W)} \qquad (1)$$

where: P_{el}- power of the fuel cell (W), U- current voltage on the fuel cell (V), I- current on the fuel cell (A).

Based on the power, it is possible to plot the mass flow of hydrogen in the fuel cell as a function of time. The mass flow rate is obtained from the following equation:

$$Q_m = \frac{P_{el}}{Q_H \cdot \eta} \qquad (\text{kg}\cdot\text{s}^{-1}) \qquad (2)$$

where: Q_m- mass flow rate of hydrogen ($\text{kg}\cdot\text{s}^{-1}$), P_{el}- power of the fuel cell (W), η- efficiency, Q_H- heat of combustion of hydrogen with a value of 142,000 kJkg^{-1}.

The efficiency value varies based on the current on the fuel cell. Efficiency values are determined by the fuel cell manufacturer. The course of the efficiency of the fuel cell depending on the actual current in the fuel cell is shown in Figure 4.

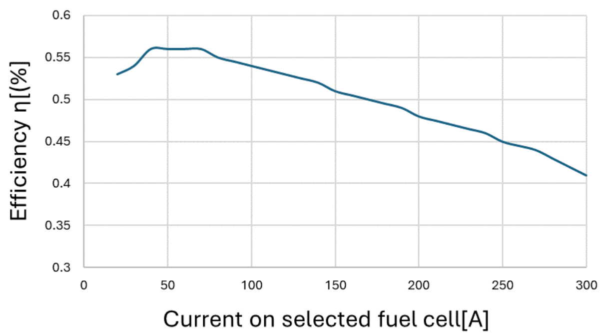
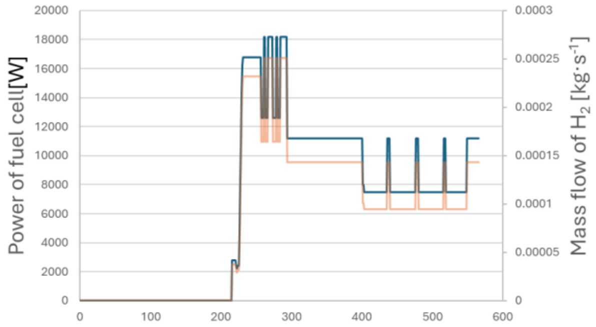


Figure 4. Efficiency of the fuel cell depending on the actual current in the fuel cell

Based on the obtained data of fuel cell power and mass flow of hydrogen, it is possible to display the time course of both monitored parameters. The curves of power and hydrogen mass flow are in Figure 5 and Figure 6.



Where: the blue curve represents the power of the fuel cell, the yellow curve represents the mass flow rate

Figure 5. Courses of fuel cell power and mass flow of hydrogen as a function of time during the second measurement from March 8, 2023

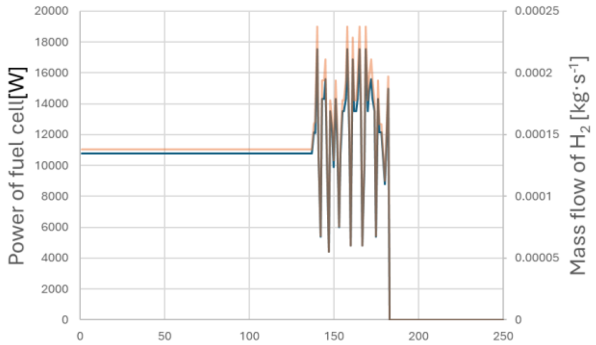


Figure 6. Courses of fuel cell power and hydrogen mass flow as a function of time during the third measurement from March 8, 2023

4 DISCUSSION

Based on the data obtained, it was found that the mass flow rate was not sufficient to make the fuel cell power similar to that after the fuel cell start-up in the system where the power value was approximately 18 kW. After a short time of approximately 5 minutes, the output power decreased to a value of approximately 11 kW. After reaching the fuel cell operating temperature, which was 66 °C and the outer circuit 60 °C, the kinetics of hydrogen desorption slowed down, thereby reducing the hydrogen mass flow rate. The power of the fuel cell ranged between 7.5 and 11 kW.

To increase hydrogen desorption from the metal alloy structure, it is necessary to modify and optimize the temperature management system in the bus. The obtained results provide a good basis for further research.

5 CONCLUSIONS

The task of this article was to design an efficient hydrogen storage system in a metal alloy structure. The first part was the design of a metal hydride storage tank according to the STN EN 13322-2 standard, which described the design and production of refillable steel bottles. Based on the mentioned standard, a metal hydride tank was designed that meets all the requirements of operational and strength parameters for a working pressure of 3 MPa and for the maximum test hydraulic pressure determined by the standard of 4.7 MPa. Subsequently, all the necessary tests mentioned in the standard were carried out.

The designed container also passed all the tests prescribed in the mentioned standard and thus it can be certified. After the certification of the metal hydride storage tank, the storage tanks were implemented in the real operation of the bus in cooperation with the company Rosero s.r.o.

Before starting the fuel cell system, a high voltage heater was started to initially preheat the liquid required to heat the metal hydride alloy tanks. Then the fuel cell system turned on. The maximum power value of the fuel cell was approximately 18 kW, the mass flow rate was approximately $2.5 \cdot 10^{-4}$ $kg \cdot s^{-1}$. After a short time after the start of the fuel cell, the power value dropped to 11 kW due to insufficient heating of the tanks, which reduced the mass flow rate of hydrogen to a value of approximately $1.3 \cdot 10^{-4}$ $kg \cdot s^{-1}$. The pressure the tank dropped to 9 bar. Based on the obtained data, it can be concluded that it is necessary to modify and optimize the temperature management of the bus for efficient operation during the winter season, which represents the future part of the research.

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