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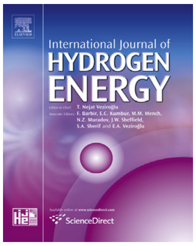

Numerical investigation of hydrogen charging performance for a combination reactor with embedded metal hydride and coolant tubes

Maha Bhouri[*], *Inga Bürger*, *Marc Linder*

Institute of Technical Thermodynamics, German Aerospace Center (DLR), D-70569 Stuttgart, Germany

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ABSTRACT

A two-dimensional model investigating the hydrogen charging process in a combination reactor filled with both $LaNi_{4.3}Al_{0.4}Mn_{0.3}$ and $2LiNH_2$-$1.1MgH_2$-$0.1LiBH_4$-3 wt.%$ZrCoH_3$ materials has been developed. The selected configuration is a cylindrical reactor of 32 cm of diameter where the MeH is filled in annular tubes separated from the complex hydride bed by a gas permeable layer. The diffusion of hydrogen towards the two storage media is ensured by filters embedded in the middle of the MeH tubes whereas the coolant tubes are placed in the centre of their triangular arrangement. Simulation results have shown that the charging process depends on the MeH reaction heat required for the initiation of the CxH reaction as well as the heat management once the complex hydride starts to store hydrogen. High hydrogen storage rates and short refueling times can be obtained by increasing the number of MeH and coolant tubes and ensuring an efficient heat removal at the peripheral area of the CxH media. A refueling time of 3 min is achieved for an optimum configuration of 49 MeH tubes and 96 coolant tubes while increasing the thermal conductivity of the CxH media to 3.5 W/(m K). Such a result could make the identified optimum configuration as a suitable hydrogen storage system for fuel cell forklift trucks since it meets the requirements of this application in terms of weight and size.

Introduction

As the international community raises its ambitions to tackle climatic and economic issues related to the use of fossil fuels, serious efforts are devoted to the building of the hydrogen economy. Firstly, research and development programs have been directed to the hydrogen-fueled light duty vehicles market. This was supported by the technical advances in fuel cell area. Nevertheless, there remain multiple challenges to be overcome before the deployment of hydrogen fuel cell cars at a commercial scale [1].

As a second step along this path, the U.S. Department of Energy (DOE), in collaboration with the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (SNL) has worked to identify early adoption markets with less stringent technical challenges than automobile sector. It has been found that specialty vehicles, stationary back-up power and portable applications present a huge market potential for the near-term development of the hydrogen technology [2,3].

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[*] *Corresponding author*. Tel.: +49 711 6862 531; fax: +49 711 6862 632.
E-mail address: maha.bhouri@dlr.de (M. Bhouri).

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For specialty vehicles, hydrogen powered fuel cell forklifts have significant benefits over existing technologies such as fossil fuel powered trucks and battery electric forklifts [4,5].

The most common battery used in the materials handling applications is the lead acid battery. The related electric forklifts are primarily designed for indoor use in order to minimize exhausts and noise, which is mandatory in such working environment. However, the long refueling time is the major issue of this technology. Indeed, the time required to change the battery is from 5 to 15 min for an automatic operation and up to 45 min for a manual one. Then, it takes 8 h to charge the battery and the same time interval to cool it down. This implies that a 24 h/7 days operation will require three batteries for each forklift. Furthermore, these operations involve the move of very heavy elements and require large battery rooms under controlled atmosphere, with the risk of hazardous materials presence. In addition, battery electric forklifts suffer from a loss of productivity as the battery discharges and show low performance under freezing conditions. Such problems could be addressed by the transition to the hydrogen powered fuel cell forklifts. Consequently, several demonstration projects have been undertaken to bring fuel cell forklifts to a commercial stage and to implement the necessary infrastructure [6–11].

The cost of the hydrogen storage and the saving in the refueling time are among the performance parameters being considered during these projects. For the majority of fuel cell forklifts tested under North American and European pilot programs, the hydrogen is supplied at pressures of 350 and 700 bar [7,10]. This corresponds to a refueling time of less than 5 min and eliminates the time consumed by the battery change-out. The choice of the pressurized hydrogen storage technique is supported by the development of the related hydrogen refueling equipment, although the infrastructure is still expensive. Furthermore, the use of compressed gaseous tank results in lighter hydrogen component system compared to the lead acid battery. Hence, additional ballast is incorporated to compensate this weight loss [7].

Solid-state hydrogen storage systems, showing poor gravimetric capacities in the case of light duty vehicles could be a suitable choice for applications such as forklift trucks since they provide weight, safety and low pressure-cost benefits over compressed gaseous storage systems. In this context, some models of fuel cell forklifts based on solid-state hydrogen storage have already been tested or are under development [7,11]. One of the first forklift trucks carrying hydrogen in a metal hydride tank has been introduced in Germany in 2000, as part of a joint project between Linde Group and Siemens AG's Power Generation Group [7]. The selected storage material is a titanium-based hydride with a charging time of 10 min. Over the past few months, researchers from Sandia National Laboratories and Hawaii Hydrogen Carriers are working together on the design of a solid-state hydrogen storage system filled with a Mischmetal-nickel-aluminium alloy [11]. The developed reactor will be integrated into the forklift fuel cell pack with the goal to show the potential storage time, cost and market growth advantages. Similarly, a wide variety of low-temperature metal hydrides extensively studied in hydrogen light duty vehicles projects could find their applications on-board forklift trucks.

Complex hydrides have high hydrogen storage capacities up to 10 wt.%. and could be cost competitive compared to some metal hydrides [12]. However, their use is hindered by their slow kinetics at practical operating conditions. Recently, a new complex hydride reactor concept has been developed to overcome this weakness. It is based on the combination of $LaNi_{4.3}Al_{0.4}Mn_{0.3}$ and Li–Mg–N–H materials. The investigation of the charging process has proven the possibility to reduce the time required for the initiation of the complex hydride reaction by 600 s while starting the loading of hydrogen at room temperature [13]. In this paper, we investigate the capability of such a complex hydride reactor concept to meet the requirements of fuel cell forklift applications in terms of refueling time and system weight and size. In the first part, the charging performance of a hydrogen storage system with embedded filters, metal hydride and heat exchanger tubes is assessed through the numerical study of different reactor configurations. Thereafter, the weight and volume of the final selected reservoir design are determined in function of the fuel cell forklifts energy requirements.

Model formulation

Description of the studied configuration

In previous studies [13], the possibility of accelerating the charging process of the complex hydride, $2LiNH_2$-$1.1MgH_2$-$0.1LiBH_4$-3 wt.%$ZrCoH_3$ through its combination with the metal hydride, $LaNi_{4.3}Al_{0.4}Mn_{0.3}$ has been proven. The studied configuration is a 50 g tubular reactor where a gas permeable separation layer (GPSL) ensures the indirect contact between the two storage media: the metal hydride at the centre of the tube, surrounded by the complex hydride. The combination reactor, initially at room temperature, is filled with hydrogen at 70 bar. Since the AB_5 material, $LaNi_{4.3}Al_{0.4}Mn_{0.3}$ is able to absorb hydrogen very quickly at these ranges of temperature and pressure, its reaction heat ensures the heat up of the complex hydride bed to temperatures above 130 °C. Furthermore, based on the kinetics measurements of the Li–Mg–N–H material at 70 bar, it has been shown that temperatures above 130 °C are required for achieving high hydrogen loading rates [14]. Accordingly, in a combination reactor, the complex hydride charging process is initiated without the need of external heat source integration. The numerical investigation of the combination reactor charging process [13] has shown that the metal hydride, $LaNi_{4.3}Al_{0.4}Mn_{0.3}$ reaches its saturated state after only 10 s transferring then its reaction heat towards the complex hydride media. As a result, the Li–Mg–N–H material starts to absorb hydrogen in the region close to the GPSL and a reaction front is developed from the core to the annulus of the reactor. As the reaction proceeds, the complex hydride reaction heat is removed by the heat transfer fluid circulating through the reactor wall. Overall, the time required for the initiation of the complex hydride reaction is reduced by 600 s although the combination reactor charging process starts from room temperature.

A subsequent study of the same configuration with different thicknesses of the MeH and CxH materials has