Design of Passive Internal Heat Transfer Intensifier for Metalhydride Vessels for Mobile Applications

Filip Duda[1*], Natália Jasminská[2], Ľubomíra Kmeťová[3], Šimon Hudák[4]

Department of Power Engineering, Faculty of Mechanical Engineering, Technical University of Košice, Slovakia
*Corresponding Author

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***Abstract*—** *For the development of modern transport systems that meet the demanding goals of reducing greenhouse gas emissions, set in the Paris Agreement from the end of 2015, it is necessary to consider new technologies and new vehicle concepts. In addition to the contractually agreed and accelerating need to contribute to significant emissions reductions, such developments would help to replace fossil fuel energy that most countries around the world are heavily dependent from. Thus, fossil fuels cannot be part of a suitable transport system.*

The aim of this work is to design an effective passive cooling system for metal hydride pressure vessel which is used for mobile applications.

***Keywords*— Passive Intensifier, Metal Hydride, Hydrogen.**

I. INTRODUCTION

A promising technological concept that meets the above requirements is the use of hydrogen in combination with fuel cells and an electric engine. Compared to battery electric vehicles, such an approach has the advantage that hydrogen cars could be driven for much longer distances without refuelling. But such a hydrogen-based mobility concept will be successfully implemented in the existing mass market only if hydrogen can be stored safely, quickly and in a technically advanced, economically efficient, and ecological way.

The biggest advantage of using hydrogen in mobile applications is the zero production of emissions (NO_x, CO_2) when it is burned in fuel cells. An important aspect of the applicability of hydrogen in mobile applications is its energy content. A kilogram of hydrogen has three times higher energy content compared to commonly used fuels such as gasoline (H2: 39.4 kWh·kg-1, gasoline: 12.9 $kWh \cdot kg^{-1}$, CNG: 15 $kWh \cdot kg^{-1}$ and LPG: 14 $kWh \cdot kg^{-1}$). In a volume comparison, the energy content of hydrogen is significantly lower than that of commonly used fuels (H2: 1.6 $kWh \cdot l^{-1}$, gasoline: 9.5 $kWh \cdot l^{-1}$, CNG: 2.5 $kWh \cdot l^{-1}$ and LPG: 7.3 $kWh \cdot l^{-1}$). Therefore, for the efficient use of hydrogen, it is important to increase its density by compression. Currently, several methods of hydrogen storage are applied in practice:

- **Compressing hydrogen gas:** it is carried out at room temperature and the maximum pressure depends on the materials from which the vessels are made. In available cars, the hydrogen pressure is at the level of 70 MPa, and for buses, the maximum pressure is reduced to 35 MPa.
- **Hydrogen liquefaction:** a very energy-intensive process with consumption of up to 15.2 kWh per kilogram of hydrogen. Liquefied hydrogen is subsequently kept in a liquid state at a temperature of -252 °C.

- **Storage of hydrogen by adsorption on the surface of solid substances**: this is a reversible way of storing hydrogen using the attractive Van der Waals interactions of atoms of a solid substance with gas molecules, which keep them on its surface. Materials that have the largest surface area are used for this storage. They are mainly porous materials such as zeolites and activated carbon. The biggest disadvantage is the need to maintain the vessel at a liquid nitrogen temperature of up to -195 °C and at a pressure of 2.5 MPa.

- **Storage of hydrogen by absorption into metal hydrides MH**: this type of hydrogen storage is the most suitable in terms of safety. This reversible process of absorption and desorption of hydrogen can be done at room temperatures and at low pressures 0.01 - 1 MPa. Biggest disadvantage is that heat is released during absorption process, and it is necessary to heat up the metal hydride while desorption process. It is compulsory to design an effective thermal management for effective utilisation of this type of storage.

As part of the work solution, the Hydralloy® alloy was chosen, the composition of which is based on MnTiVFeZr (Fig. 1). The composition of this alloy in wt.% is shown in TAB. 1.

FIGURE 1: Applied metal hydride alloy Hydralloy®

TABLE 1
COMPOSITION OF APPLIED METAL HYDRIDE ALLOY HYDRALLOY® IN VESSELS

Element	wt.%
Mn	51,50
Ti	27,20
V	14,15
Fe	3,04
Zr	2,87
Ti+Zr	30,07
V+Fe	17,19

For the design, an alloy in the form of a powder (FIG. 1) is considered, whose grain size ranges from 0-2 mm. In FIG. 2 shows the PCI curve of three repeated measurements of the applied MH alloy at room temperature.

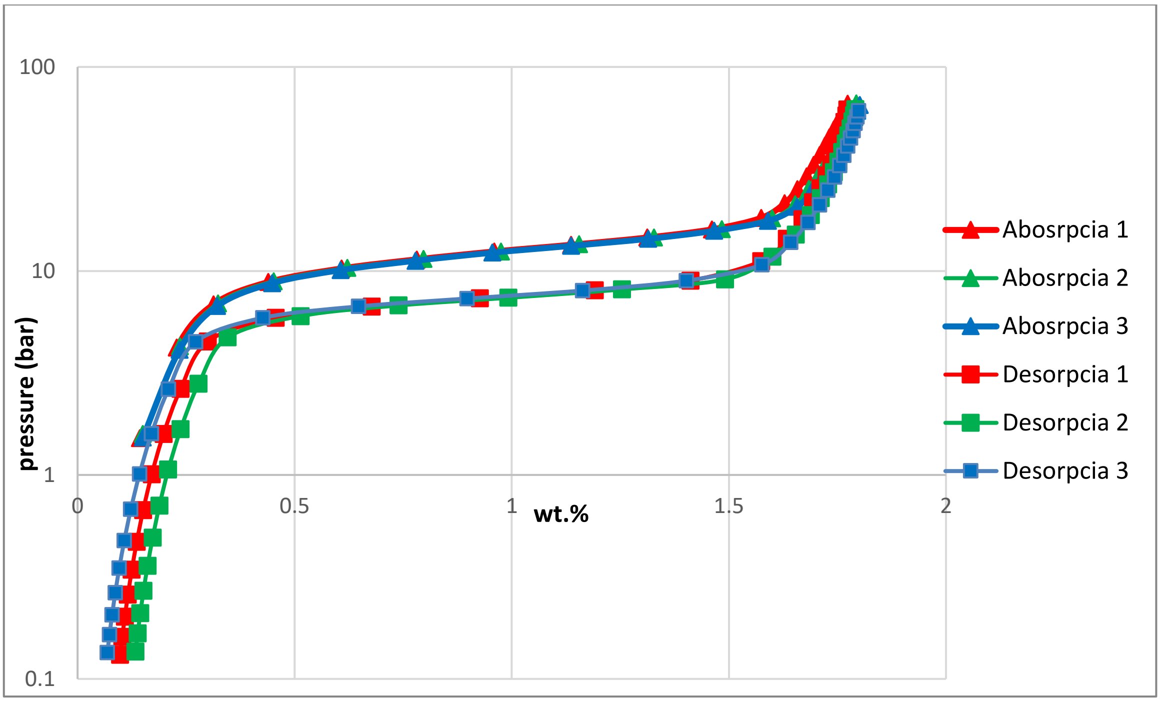

FIGURE 2: PCI curve of absorption and desorption of Hydralloy® alloy at room temperature of 3 different measurements

It can be seen from the PCI curves that the capacity of stored hydrogen at a temperature of 20 °C and a pressure of $65 \cdot 10^5$ Pa is expressed by the ratio of the weight of the absorbed hydrogen to the weight of the alloy at the level of 1.8%. Hydrogen absorption into the MH alloy structure occurs at a pressure of $11.95 \cdot 10^5$ Pa. Desorption of hydrogen from the structure of the MH alloy occurs at a pressure of $7.33 \cdot 10^5$ Pa.

Since heat is released during the absorption of hydrogen into the intermetallic structure of the metal alloy, it is necessary to remove the generated heat. The amount of released heat depends on the type of alloy used, for example, with MH alloy based on LaCeNi, 1 MJ of heat is released when 1 m^3 of molecular hydrogen is absorbed. This heat can be used in a vehicle or other mobile heating device. During the desorption of hydrogen from the structure of the MH alloy, it is necessary to bring the same amount of heat. Based on the above facts, in addition to the design of MH storage tanks, it is necessary to consider the design of temperature management, which allows heat to be removed as well as supplied.

If the MH vessel does not have temperature management and does not contain the possibility of removing the generated heat from the core of the vessel, the temperature of the MH alloy increases. As the temperature increases, the equilibrium pressure increases and the kinetics of absorption decreases. When hydrogen is desorbed from the MH reservoir without the use of forced heat supply, the temperature of the alloy drops below the ambient temperature, which is caused by absorbing heat at the expense of the internal energy of the alloy, since the heat obtained through the shell from the surroundings is insufficient, especially with larger hydrogen withdrawals.

As the temperature of the alloy decreases, the equilibrium pressure in the reservoir also decreases, and if its value falls below the minimum pressure necessary for subsequent use, the entire system may become inoperable. For these reasons, research and subsequent implementation of an internal heat exchanger or heat transfer intensifier to MH storage tanks is essential. At the same time, the heat transfer intensifiers participate in equalizing the temperature field in the volume of the powder alloy, which has a large reaction surface formed by the outer surface of the metal alloy grains.

II. DESIGN OF INTERNAL HEAT TRANSFER INTENSIFIER

Since in the process of absorption storage of hydrogen in a metal hydride vessel, due to the dissociation of the hydrogen molecule and the diffusion of H_2 atoms into the interstitial space of the crystal lattice of the metal, thermal energy is generated, it is necessary to ensure the cooling of the reservoir to eliminate pressure and temperature fluctuations. On the other hand, during the desorption of hydrogen from the metal alloy, it is necessary to heat the vessel to maintain the kinetics of the process.

The metal hydride reservoir is cooled by a passive and active element. The active cooling element is the cooling liquid that is in the space between the primary vessel and the case. A passive cooling element is a heat transfer intensifier located inside the primary reservoir that serves to dissipate the heat generated during hydrogen absorption into the metal alloy structure. By optimizing the shape of the geometry of the intensifier, it is possible to intensify the removal of heat from the reservoir core, which would improve the process of hydrogen absorption.

The geometry of the designed intensifier consists of five main and ten secondary ribs. The secondary ribs are connected to each other by primary ribs of a circular cross-section, which describes the inside diameter of the primary vessel shown in FIG. 3. The gap between the primary vessel and the intensifier is 1.

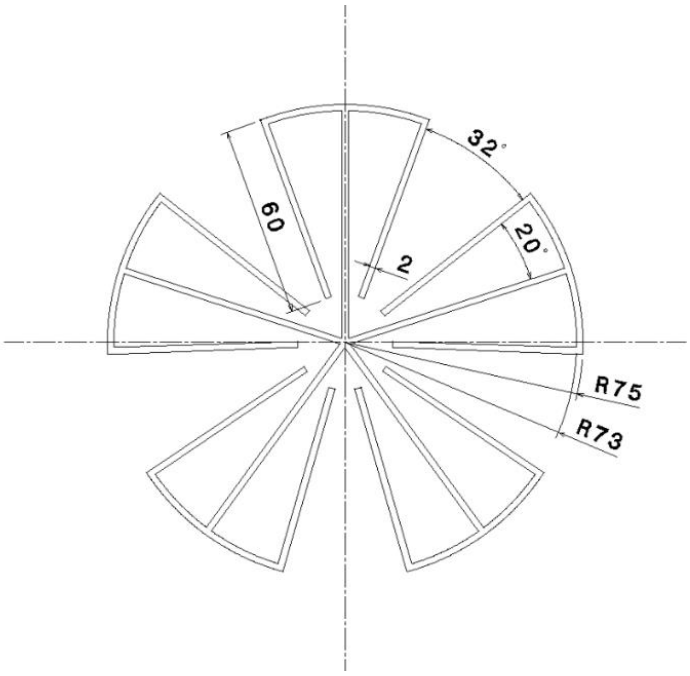

FIGURE 3: Design of internal heat transfer intensifier

In the design of the heat transfer intensifier, aluminium was used due to its good thermal conductivity of 237 $W \cdot m^{-1} \cdot K^{-1}$.

III. SIMULATION RESULTS

The temperature field in the cross-section of the vessel under investigation is shown in FIG. 4. The maximum temperature in the vessel after 1200 s which represents the time of refuelling was 89.53 °C. The hottest spots in the metal hydride were in the region between the secondary ribs. Thus, the heat is effectively removed from the core of the vessel towards the inner shell. In FIG. 5 shows the courses of maximum and minimum temperatures in the studied storage vessel after 1200 seconds of filling. On the curve of the maximum temperature, it is possible to observe the rising tendency of the temperature during almost the entire simulation, the temperature is stable in the last 200 s. The minimum temperature curve does not change from almost halfway through the simulation and remains at the same value of 30.13 °C until the end of the simulation. In FIG. 5 also shows the difference between maximum and minimum temperatures in ΔT.

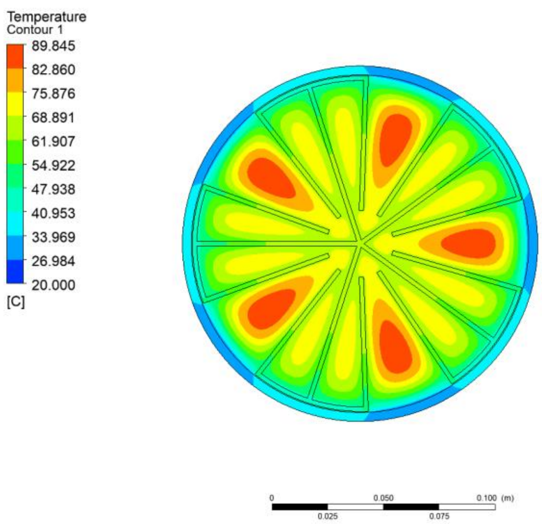

FIGURE 4: Generated temperature field after 1200 seconds of vessel filling.

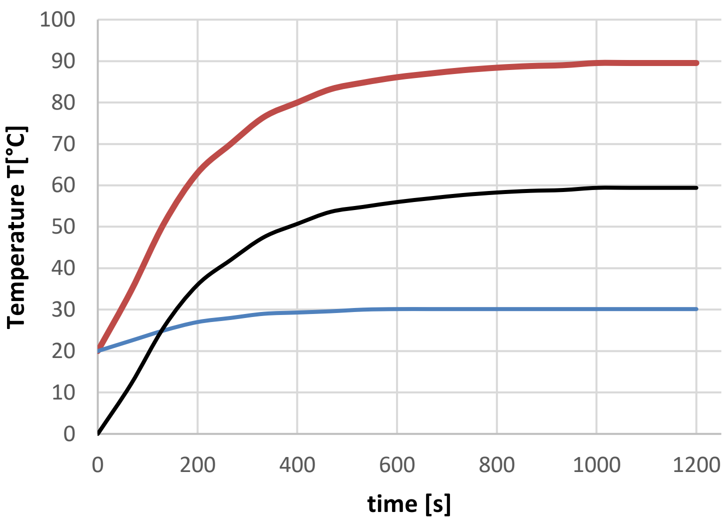

FIGURE 5: Course of minimum (blue) and maximum (orange) temperatures on the studied vessel

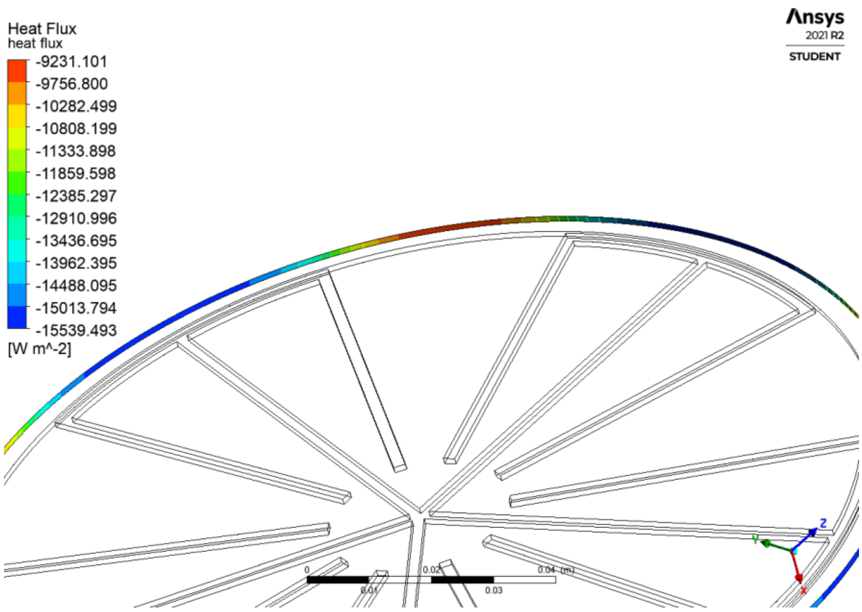

FIGURE 6: Heat removal by cooling

FIG. 6 shows the removal of heat from the metal hydride vessel by cooling around the perimeter of the steel casing. The greatest values of heat dissipation are found in the places of the primary ribs.

IV. CONCLUSION

The goal of the simulation in the ANSYS CFX program was to design an internal heat transfer intensifier that will effectively remove heat from the core of the metal hydride storage vessel to the outer shell, where the storage vessel is cooled by a cooling liquid. The simulation results showed that the designed intensifier achieves optimal values in all areas of investigation.

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