Design of internal heat transport intensifier for metal hydride storage tank

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Abstract

The present article deals with potential improvement of heat removal from the centre of a metal hydride tank towards the tank's periphery while using passive heat transfer modules. Passive cooling elements are used in order to improve heat removal from the centre of a tank towards its peripheral parts. This increases the homogeneity of the thermal field in a tank's cross-section, which is perpendicular to the longitudinal axis. Moreover, the use of such elements improves the kinetics of hydrogen absorption into an alloy, in particular by prolonging the time to an equilibrium temperature of the alloy for a particular equilibrium pressure, which may shorten the time to a tank being 100% filled with hydrogen. The article describes four different designs of internal heat transfer intensifiers, which are aimed at improving the thermal field distribution inside the tank and their theoretical impact on the thermal field, which was examined using Ansys CFX software.

Keywords: hydrogen; metal hydrides; heat exchanger; Ansys CFX.

1. Introduction

Hydrogen is the lightest chemical element, which forms as much as two thirds of all the mass in the universe. It is the third most frequent element on Earth despite the fact that it hardly exists as an individual molecule because it is highly reactive and instantly binds to form compounds. Hydrogen is present everywhere, either in form of water, natural gas or various higher forms of hydrocarbons. Combustion of pure hydrogen does cause any kind of environmental pollution. It is a zero-emission substance, which is not toxic and has no odour. It offers a wide range of applications in the transportation industry, power engineering and in many other industries. Its potential for the future consists also in applications in transportation and use of energy, as an important carrier of pure energy. Hydrogen existing in form of hydrocarbons is a fuel rich in energy.

2. Hydrogen storage in metal hydrides

Hydrogen storage is a very important component of the hydrogen management system. Very low density, small-size molecules and a wide explosive range of hydrogen represent the negative factors which make hydrogen as a fuel difficult to store and distribute. Although hydrogen exhibits higher specific heat capacity than other fuels, hydrogen storage systems are much more complex and more prone to mechanical damage than other energetically adequate systems for the storage of fossil fuels.

The safest hydrogen storage methods include binding hydrogen in form of metal hydrides. Some metals and metal alloys form hydrides and are capable of storing large amounts of hydrogen. Hydrogen storage in metal hydrides is based on the properties of metals which are able to absorb hydrogen atoms in their metal lattice. Binding hydrogen is an exothermic process so the metal alloy powder must be cooled while a tank is being filled. By contrast, when hydrogen is released, metal hydride must be heated because it is an endothermic process. This process may be conducted repeatedly without any loss of capacity [1].

$$\mathrm{M} + \frac{x}{2}\mathrm{H}_2 \leftrightarrow \mathrm{MH}_x + \mathrm{heat} \tag{1}$$

wherein M is metal; H is hydrogen; x is a mole fraction of hydrogen; and MH is a metal hydride.

3. Designs of an internal heat exchanger

The proposed design of a metal hydride tank consists of a cylindrical double-jacket tank and a heat transfer intensifier, which is installed inside the tank. A diameter of the tank is 159 mm and its length is 1 m. The tank is filled with a $La_{0,85}Ce_{0,15}Ni_5$ alloy. Cooling fluid flows along the external surface of the tank and removes a large amount of heat released during absorption. The tank is made of stainless steel, class 316l (Fig. 1).

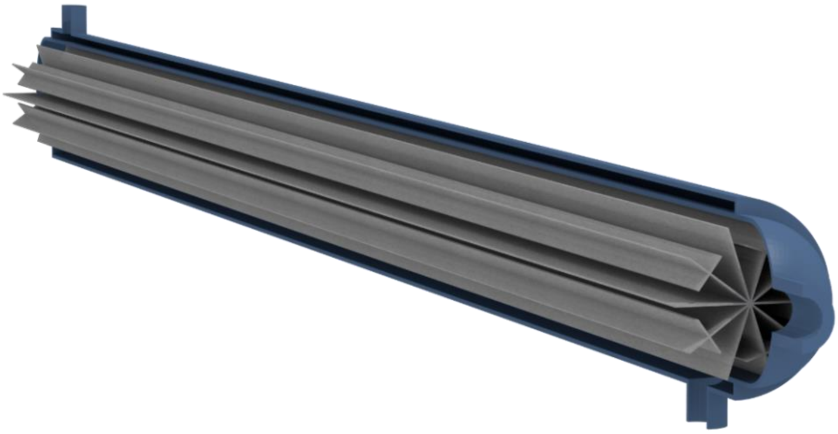
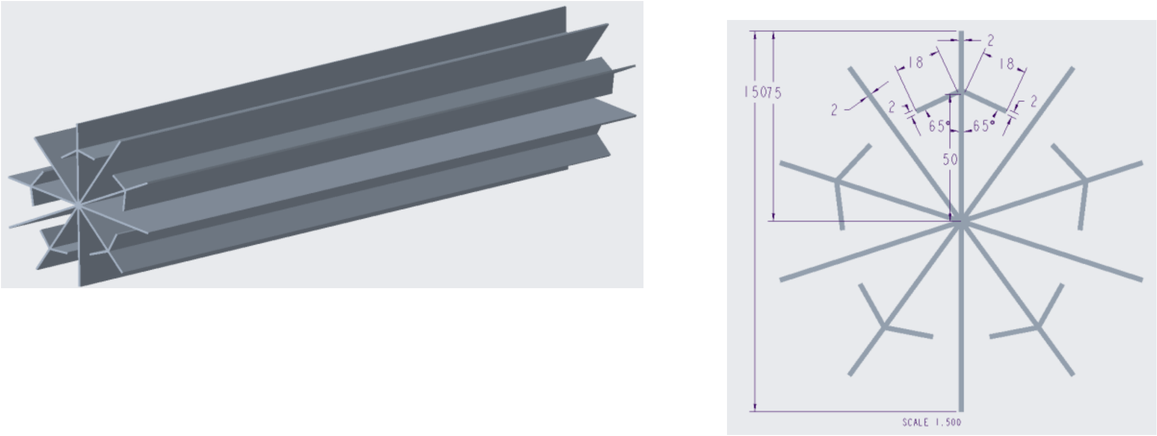


Figure 1. Proposed design of a metal hydride tank.

Inside the tank, there is an aluminium heat exchanger, referred to as an intensifier, which is aimed at increasing the removal of heat from the tank centre towards the jacket, where the tank is cooled by water. By changing the geometry of the intensifier, it is possible to improve the heat removal from the tank, and hence improve the absorption process. When designing an internal heat exchanger, it is necessary to consider the requirement for maintaining the ratio of a metal hydride storage capacity to a volume of aluminium. In order to ensure good thermal conductivity of the intensifier, it was made of aluminium.

Fig. 2 shows Design 1 of the geometry of the internal exchanger in a cross-section. This geometry consists of ten primary fins and ten secondary fins. The secondary fins are directed towards the centre of the tank.



Internal heat intensifier Design geometry in a cross-section

Figure 2. Design 1 of the intensifier basic geometry.

Design 2 of the intensifier geometry consists of eight primary fins and eight secondary fins. The secondary fins are directed towards the tank jacket at an angle of 45° (Fig. 3). Design 3 consists of five primary fins and ten secondary fins. The secondary fins are connected to the primary fins through a circular segment that copies the shape of the tank jacket. The purpose of such an arrangement was to increase the heat transfer area near the tank wall. A gap between the intensifier and the wall is 1 mm wide (Fig. 4).

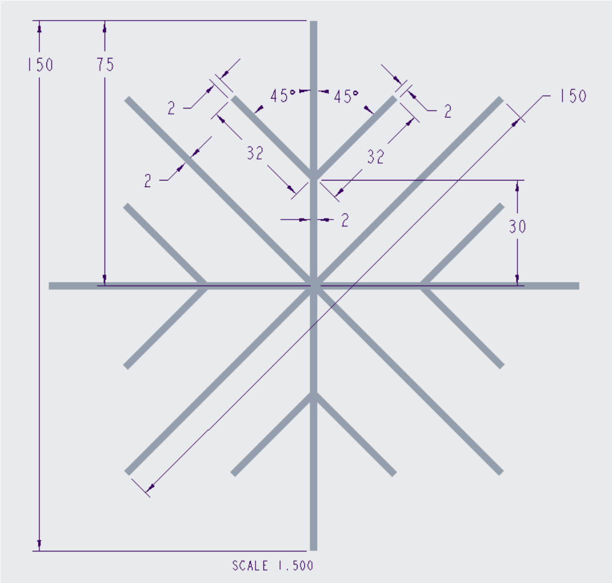


Figure 3. Geometry of Design 2 of an intensifier in a cross-section.

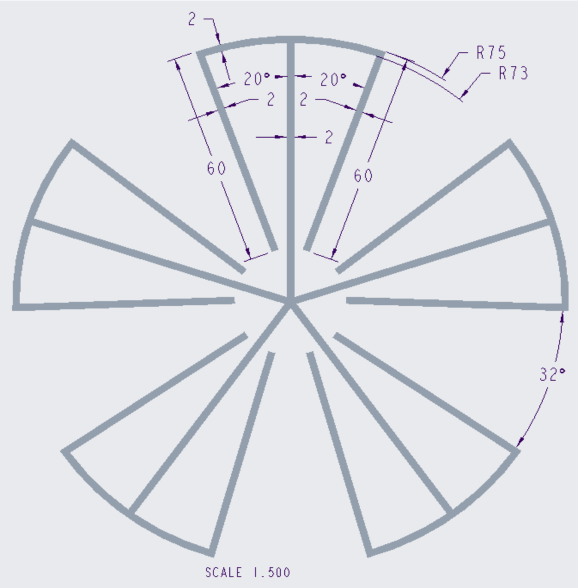


Figure 4. Geometry of Design 3 of an intensifier in a cross-section.

The geometry of Design 4 of the internal heat exchanger consists of eight primary fins and eight secondary fins. The secondary fins are connected to four primary fins in the same manner as in Design 3. The spacing of the secondary fins is 45°. A gap between the intensifier and the tank wall is 1 mm wide (Fig. 5).

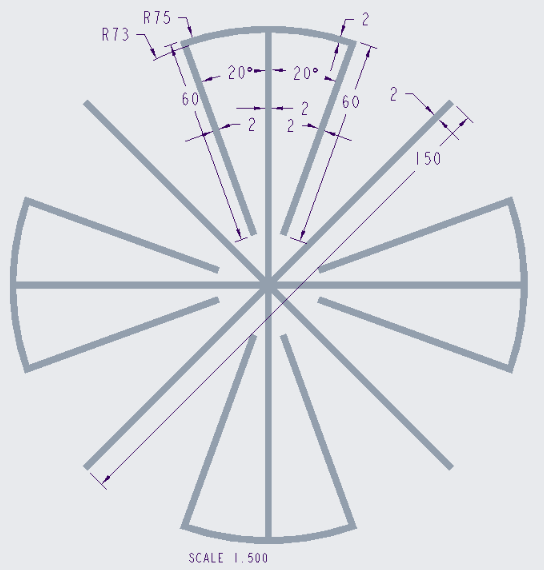


Figure 5. Geometry of Design 4 of the intensifier in a cross-section.

4. Numerical simulations of the intensifier designs

The thermal field distribution in the tank in a tank cross-section, which is perpendicular to the tank's longitudinal axis, was investigated using ANSYS CFX software.

The tasks which include a complex geometry and different material properties can almost never be solver analytically. The finite volume method is used when solving the tasks concerning the fluid flow and heat transfer. The underlying principle of this method is that a model is divided into a finite number of volumes and a subsequent calculation is made across the boundary points of such volumes [5].

The simulations were aimed at investigating individual designs in terms of heat removal from the centre of a metal hydride tank, as well as heat transfer facilitated by the cooling fluid flowing along the external surface of the jacket.

Figures 6 through 9 show the thermal fields of the individual designs of a metal hydride tank in a cross-section. The simulations were carried out within the period of 20 minutes, at an input cooling fluid temperature of 20 °C and a fluid flow rate of 0.3 m·s^{-1}. The tank filling time was 1,200 s. Each of the designs exhibited a different amount of the generated heat due to different ratios of a volume of the stored metal hydride to a volume of aluminium.

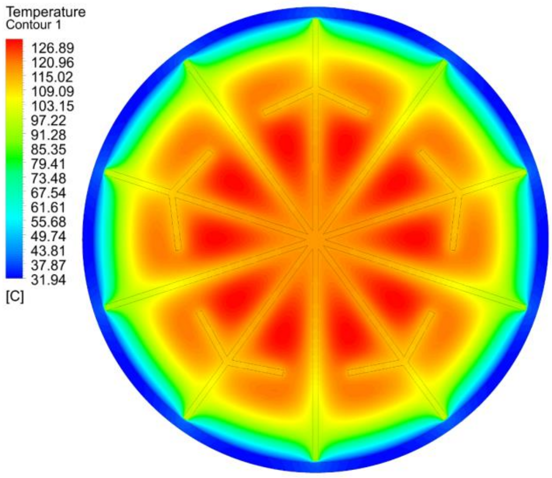


Figure 6. Thermal field of Design 1.

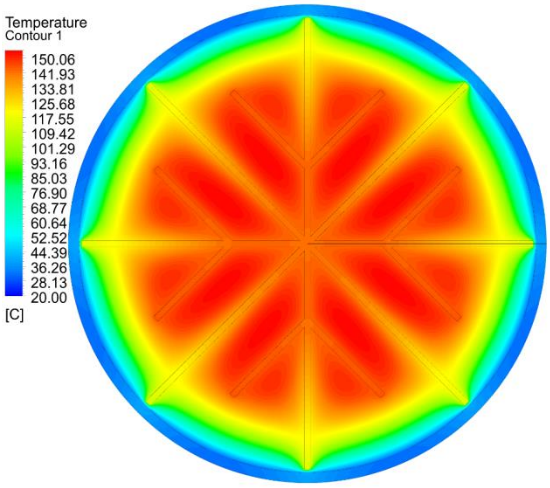


Figure. 7 Thermal field of Design 2.

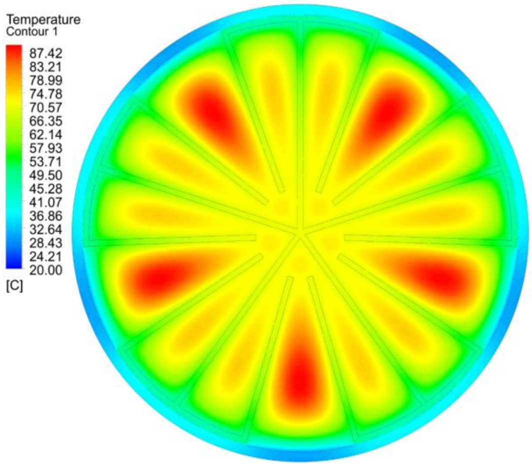


Figure. 8 Thermal field of Design 3.

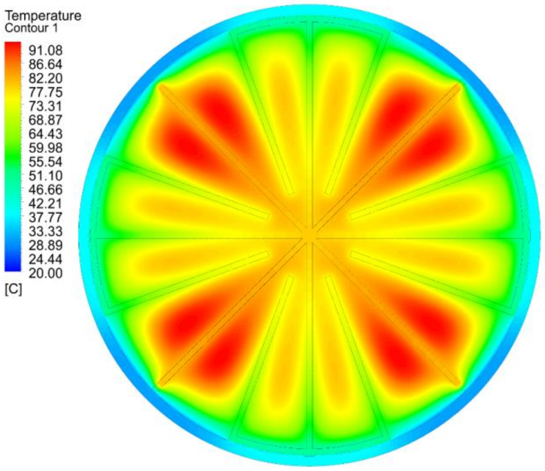


Figure. 9 Thermal field of Design 4.

The factor which was important for comparing all the four designs was a maximum temperature achieved during the tank filling. With a rising temperature in a metal hydride tank, the absorption kinetics slowed down while the tank filling pressure was maintained at a constant level. Once the equilibrium pressure and temperature were achieved, the alloy stopped absorbing hydrogen. This fact was neglected in the initial analysis of the basic thermal conductivity characteristics of the individual designs of the intensifier geometry that represent the subject of this article.

The results of the numerical simulations indicate that an optimal position of a heat transfer intensifier significantly improves the thermal filed distribution in a metal hydride tank intended for hydrogen storage. Different shapes of intensifiers have different effects on the thermal field distribution, as may be concluded from the simulation results. Apparently, the most appropriate design was Design 3, in which the high-temperature zones exhibited lower volumes and a lower maximum temperature than that of the remaining three designs. A disadvantage of this particular shape is a lower storage capacity, which is caused by a smaller volume of the metal hydride alloy in the tank volume. Therefore, an intensifier should be designed with optimal proportions to avoid significant loss of the storage capacity caused by the reduced inner space due to the presence of an intensifier.

5. Conclusion

Hydrogen storage in metal hydrides is associated with the production of a large amount of thermal energy, which must be removed from the storage system in order to ensure a continuous hydrogen storage process. With an increasing volume and especially a diameter of a tank, it is more problematic to remove heat from the centre of a tank. The results of the simulations showed that even though the use of passive heat removal systems reduced the total volume of the alloy in the tank, the heat removal from the tank centre was improved; as a result, this not only improves the storage kinetics, but also prevents local overheating, which may damage the alloy. The simulations indicated that the heat removal from the areas around the central longitudinal axis of the tank was significantly affected by a material an shape of an internal passive intensifier, while the fins must be positioned so that they remove as much heat as possible from the critical zones.

6. Acknowledgement

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5. References

[1] AFZAL, M., MANE, R., SHARMA, P. (2017). Heat transfer techniques in metal hydride hydrogen storage: A review. In: International Journal of Hydrogen Energy, 42 (52), 2017. p. 30661 – 30682.

[2] CHIBANI, A., BOUGRIOU, CH., MEROUANI, S. (2018). Simulation of hydrogen absorption/desorption on metal hydride $LaNi_5$-H_2: Mass and heat transfer. In: Applied Thermal Engineering, 142, 2018. p. 110–117.

[3] LIPMAN, E. T., WEBER, Z, A. (2018). Fuel Cells and Hydrogen Production. New York: Springer Science+Business Media, 2018. ISBN 978-1-4939-7789-5.

[4] STOLTEN, D. (2010). Hydrogen and Fuel Cells, Weinheim: Wiley, 2010, 908 p. ISBN 978-3-527-

32711-9.

[5] BRESTOVIČ, T., JASMINSKÁ N. (2015). Numerické metódy a modelovanie v energetike, Košice, SjF TU v Košiciach, 2015. ISBN 978-80-553-0223-2.