DEVELOPMENT OF AUTOMOTIVE LIQUID HYDROGEN STORAGE SYSTEMS

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ABSTRACT

Liquid hydrogen (LH_2) takes up less storage volume than gas but requires cryogenic vessels. State-of-the-art applications for passenger vehicles consist of double-wall cylindrical tanks that hold a hydrogen storage mass of up to 10 kg. The preferred shell material of the tanks is stainless steel, since it is very resistant against hydrogen brittleness and shows negligible hydrogen permeation. Therefore, the weight of the whole tank system including valves and heat exchanger is more than 100 kg. The space between the inner and outer vessel is mainly used for thermal super-insulation purposes. Several layers of insulation foils and high vacuums of 10^{-3} Pa reduce the heat entry. The support structures, which keep the inner tank in position to the outer tank, are made of materials with low thermal conductivity, e.g. glass or carbon fiber reinforced plastics. The remaining heat in-leak leads to a boil-off rate of 1 to 3 percent per day. Active cooling systems to increase the stand-by time before evaporation losses occur are being studied. Currently, the production of several liquid hydrogen tanks that fulfill the draft of regulations of the European Integrated Hydrogen Project (EIHP) is being prepared. New concepts of lightweight liquid hydrogen storage tanks will be investigated.

INTRODUCTION

Alternative fuel and drive train solutions represent one of the biggest challenges for the vehicle of the future. In response to the greenhouse effect, increasing costs and limited sources of fossil fuels, new options of clean and renewable fuels are under investigation. Current research activities related to hydrogen as an energy carrier indicate that the concept of hydrogen economy has considerably gained in credibility in recent years. Hydrogen releases energy through a chemical reaction with oxygen. This energy can be used for powering vehicles either in a fuel cell delivering electricity output or in an internal combustion engine similar to present vehicles. Nevertheless, one of the greatest technological barriers to the introduction of hydrogen as an energy carrier is an efficient and safe storage system. Car manufacturers, suppliers, and research institutes investigate technologies to store hydrogen as compressed gas, as cryogenic liquid, or in solid materials. None of these technologies satisfies all of the hydrogen storage attributes sought by manufactures and end users. Compared to other technologies, the advantages of liquid hydrogen are the high energy density at low pressure as shown in FIGURE 1 and the favorable transportation characteristics [1]. In order to archieve the same energy density as with liquid hydrogen at an operational pressure of 0.5 MPa, gaseous hydrogen must be compressed up to about 200 MPa. Hence, the low pressure allows geometries other than spheres or cylinders and facilitates a better integration of the storage vessel into the vehicle. One drawback of liquid hydrogen storage systems is the boil-off due to the finite heat inleak to the isolated container. Therefore, investigations of advanced cooling systems propose an increase of time before evaporation losses occur to more than 12 days [2].

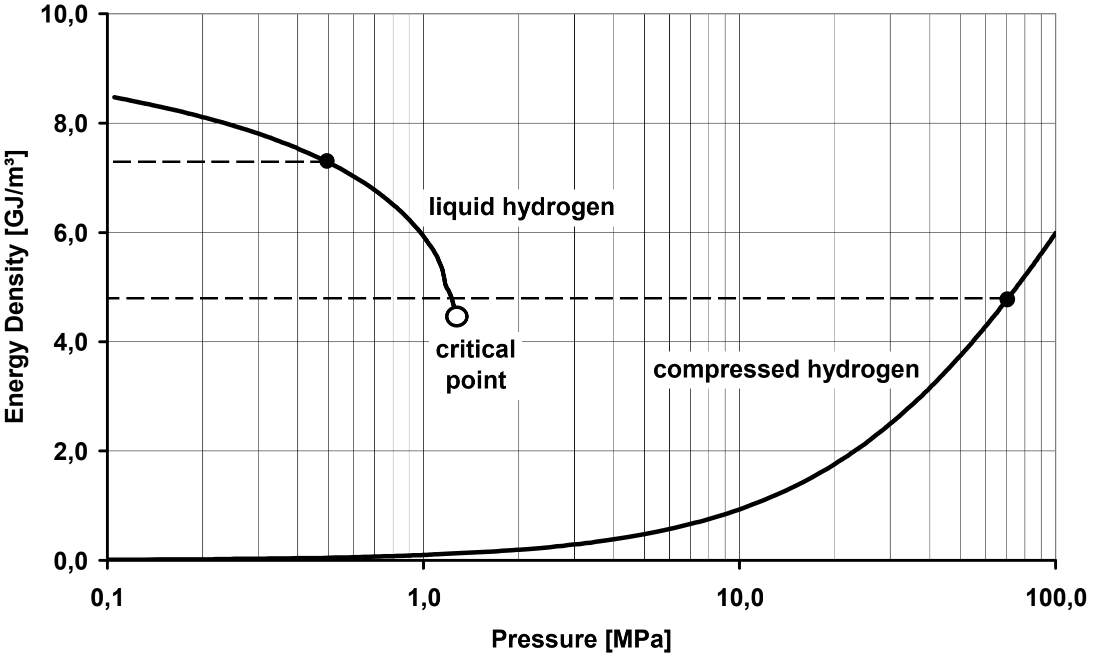

FIGURE 1. Energy density of liquid and gaseous hydrogen as a function of pressure

Cars represent the ultimate market for manufacturers of hydrogen storage systems due to the quantities involved worldwide. They also pose some of the greatest challenges to commercialization, including their relatively small size, the vast fuelling infrastructure required, and the inconsistent maintenance habits of the public at large. In addition, performance and reliability expectations are high. Cost issues will be addressed by selecting automated production technologies and scaling effects in mass production.

STATE OF THE ART

State of the art liquid hydrogen storage systems, as shown in FIGURE 2, consist of double-wall cylindrical tanks that hold a hydrogen storage mass of about 10 kg. Preferred shell materials are stainless steel or aluminum alloy, since they are very resistant against hydrogen brittleness and show negligible hydrogen permeation. Low specific weight combined with high modules and strength as well as high coefficients of thermal expansion and very good characteristics of heat conductivity have given aluminum a major role in the aerospace and automotive industries. In case of stainless steel, the minimum wall thickness of the shells is between 2 and 4 mm according to the regulation for cryogenic vessels. Therefore, the weight of the whole tank system including valves and heat exchanger is about 150 kg.

The space between the inner and outer vessel is mainly used for the thermal super insulation. The heat entry by thermal radiation is reduced by about 40 layers of super insulation foils with an area weight of 1.5 to 3.0 kg/m², composed of reflective aluminum or aluminized polymer foils separated by glass fiber spacers. The vacuum pressure of about 10^{-3} Pa at 20 K reduces the thermal convection to a minimum. The support structures, keeping the inner tank in position to the outer tank, are made of glass or carbon fiber reinforced plastics. If the vehicle is not used for more than three days, the heat entry leads to a boil-off rate of 1 to 3 % per day.

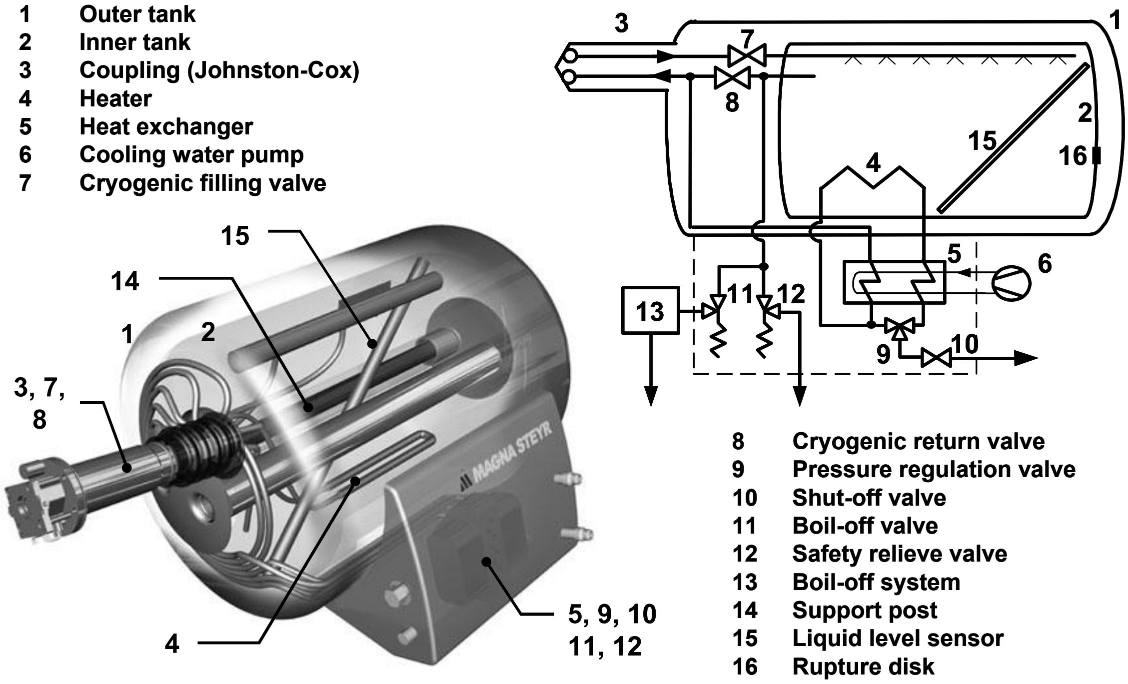

FIGURE 2. State of the art liquid hydrogen storage

During the filling procedure both valves, the cryogenic filling valve (7) and the cryogenic return valve (8), are opened. Liquid hydrogen flows from the filling station via a Johnston-Cox coupling (3) and the cryogenic filling valve into the inner vessel (1). In order to keep the inner tank pressure low, evaporated gaseous hydrogen leaves the inner tank via the cryogenic return valve and flows back to the filling station. After finishing the filling procedure, both cryogenic valves will be closed. For hydrogen extraction, the cryogenic filling valve remains closed while the cryogenic return valve is open. Gaseous hydrogen leaves the inner tank to the cooling water heat exchanger (5). Hydrogen heats up above ambient temperature and flows further into the pressure regulation valve (9). If the inlet pressure is above the defined set pressure of the pressure regulator, the partial flow inlet will be closed and no hydrogen can pass through the tank heater (4). Therefore, no additional heat will be led to the inner tank heater and the pressure will decrease. During stand-by, both cryogenic valves are closed. During long-term parking the hydrogen pressure in the inner tank rises until the boil-off valve (11) will limit the boil-off pressure. Overpressure in the inner tank must not open the cryogenic valves. In case of a fault of the boil-off valve the pressure in the inner tank rises until the safety relief valve (12) opens. The last device that prevents the explosion of the tank is a rupture disk (16), which is needed in case of a default of the safety relief valve.

In Europe, prototype liquid hydrogen tanks for fuel cell and combustion engine powered vehicles are built by Messer-Griesheim, Linde, and Air Liquide. The development of liquid hydrogen tanks for multiple productions is in preparation at Magna Steyr.

AUTOMOTIVE REQUIREMENTS

Alternative powered vehicles are subject to comparison with petrol and gasoline powered vehicles. In addition to conventional specification characteristics like maximum power and range, customers will pay attention to cost performance ratio and possible tax abatements.

As long as cars follow conventional design rules the fuel storage system must fit into the clearances as shown in Figure 3. In case of an accident, the storage system shall be placed as safely as possible. This aspect reduces the possibilities to integrate the system into the vehicle.

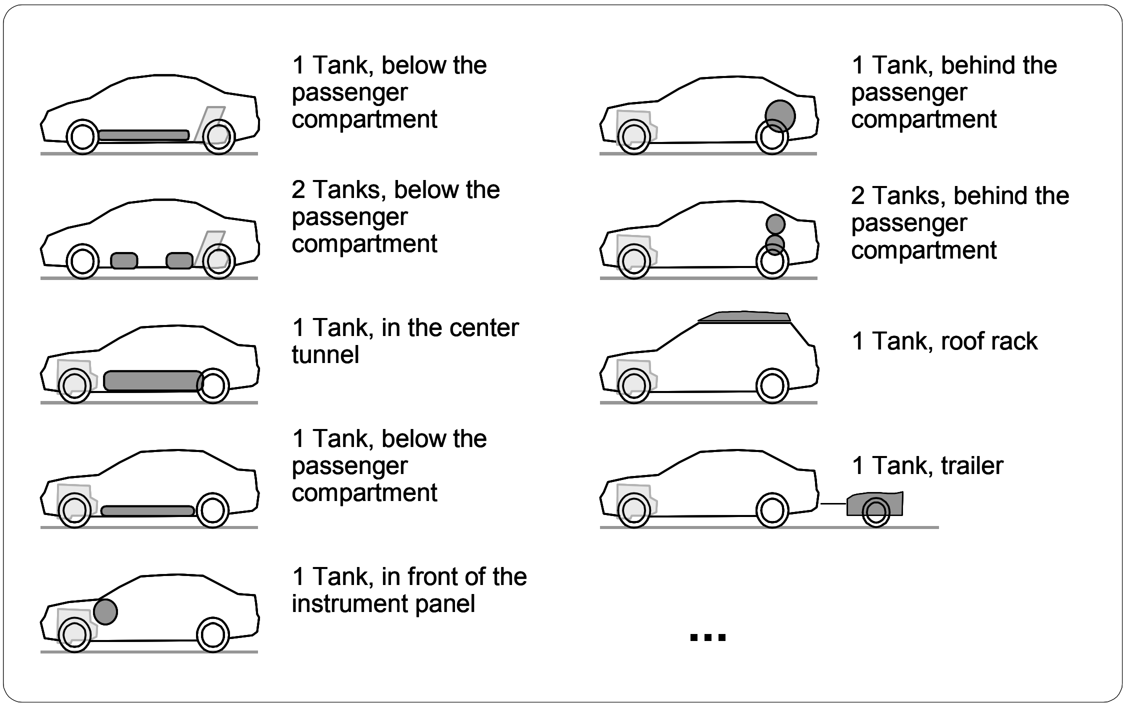

FIGURE 3. Possible tank locations in passenger cars

Car storage systems require a fail-safe design since drivers usually are not experienced in handling hydrogen. Therefore, Failure Mode and Effect Analysis (FMEA) performed on critical components shall minimize the occurrence of malfunctions of the system.

Based on pressure vessel regulations the European Integrated Hydrogen Project (EIHP) defines standards to design specific components of motor vehicles using liquid hydrogen. The current version, Revision 14, only deals with metallic vessel materials. The container and its equipment shall function in a correct and safe way. It shall reliably withstand the electrical, mechanical, thermal and chemical operating conditions and it shall remain gastight. In case of an accident with a full hydrogen tank, the hydrogen container including the safety devices affixed to it must be mounted and fixed in a way that the acceleration of 200 m/s^2 in the direction of travel and 80 m/s^2 horizontally perpendicular to the direction of travel can be absorbed without damage to the safety-related parts. No uncontrolled release of hydrogen is allowed.

Operational excitation frequency ranges between 0 and about 30 Hz. Therefore, the natural frequency of safety components must be at least 40 Hz in order to avoid damage due to resonance effects. Durability and lifetime expectations depend on the strategy of the car manufacturer.

End-of-life vehicle directives require an efficient recycling process with a focus on the separation of materials and components that are used in the production of a liquid hydrogen vessel.

COMPONENT DESIGN

Typically, an on-board liquid hydrogen storage system contains the following components: a container with support posts, a refueling connection or receptacle, a pressure relief device, an automatic shut-off valve, a flexible or rigid fuel line, fittings or screwed connection systems, a hydrogen conversion system, a safety instrument system, a fuel level sensor or flow rate sensor to calculate the fuel level, a fuel level indicator, and a boil-off management system. According to the EIHP specification, most of these components must have a type approval. The specific component design of the storage system is based on the vehicle safety concept. In accordance with the plant design, the fault hazard analysis for an uncontrolled hydrogen accident requires a failure-rate lower than 10^{-9} per hour for the whole storage system.

Components in contact with hydrogen shall withstand a test pressure of 1.5 times its maximum allowable working pressure with the outlets of the high pressure part plugged without any visible evidence of leak or deformation. Hence, the component must not show any visible evidence of rupture or cracks. In components that are subjected to frequent load cycles, all situations shall be avoided that can lead to local fatigue since hydrogen is known to significantly accelerate a possible development and propagation of fatigue cracks in a structure. Components installed inside the hydrogen container cannot be exchanged and shall be designed maintenance-free for a lifetime of at least 10 years.

The thermal insulation between the inner and the outer tank plays a major role. It is a typical spin-off from space technology that consists of several layers of Multi-Layer-Insulation foils at a high vacuum of about 10^{-3} Pa. In order to speed up the evaporation process and for the long-time stabilization of the high vacuum molecular sieves and non-evaporable getters are required. The inner supports are designed to keep the inner container in position to the outer container. On the one hand, the inner supports of the full container shall resist the apparent acceleration during operation and crash forces in case of an accident without rupture. On the other hand, the heat in-leak to the inner tank has to be minimized. Depending on the vessel geometry, preferred materials are co-axial tubes or loops of glass-fiber or carbon fiber reinforced plastics with high mechanical strength and low thermal conductivity.

FIGURE 4 shows the cost distribution for a liquid hydrogen prototype storage system. The price is mainly determined by component and assembly costs. A cost degradation is strongly linked with the degree of automation because of the use of efficient mounting devices. Hence, it should point out that moderate investments will already increase the degree of automation substantially from currently 3%.

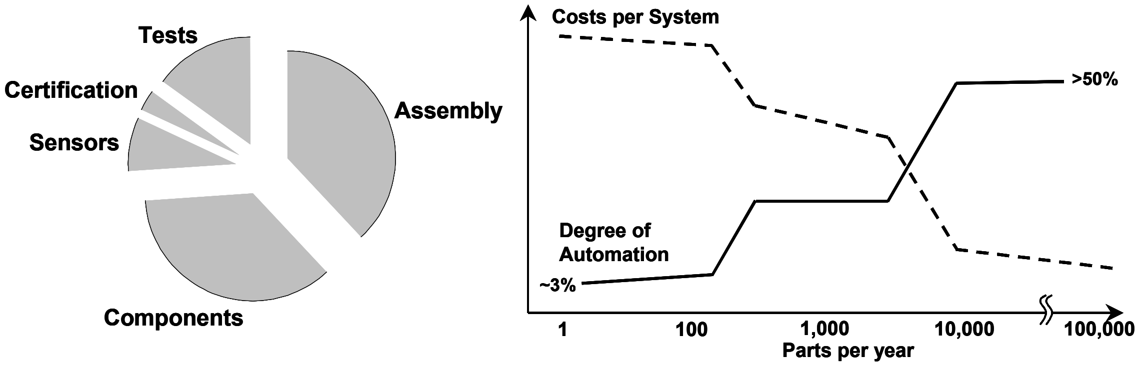

FIGURE 4. Cost issues for a Liquid hydrogen storage system

FORECAST

A great challenge for future generations of hydrogen-powered vehicles is the development of lightweight storage systems with conformable tank shapes that can be adapted to the space available in various vehicle structures. New concepts that make it possible to get shape geometries more suited to vehicle design (e.g. free-form tanks) require expensive reinforcement measures to reduce the weight of the storage system. This is possible in the case of cryogenic storage because of the low working pressure compared to high-pressure storage systems. There is great potential to reduce weight by using new composite materials, with which a specific energy storage mass similar to a conventional fuel tank can be achieved. During operation, the temperature and pressure shall be in the range of 20 to 358 K and 0 to 6 bar (a), respectively. Furthermore, if fiber composite materials with the appropriate orientation of the winding/fiber are used, greater strength can be achieved than with stainless steel, which would enable manufacturing of new - other than cylindrical - tank geometries .

ACKNOWLEDGMENTS

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