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The potential for avoiding hydrogen release from cryogenic pressure vessels after vacuum insulation failure

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ABSTRACT

This paper presents an analysis of vacuum insulation failure in an automotive cryogenic pressure vessel (also known as cryo-compressed vessel) storing hydrogen. Vacuum insulation failure increases heat transfer into cryogenic vessels by about a factor of 100, potentially leading to rapid pressurization and venting of the cryogen to avoid exceeding maximum allowable working pressure (MAWP). Hydrogen release to the environment may be dangerous, especially if the vehicle is located in a closed space (e.g. a garage or tunnel) at the moment of insulation failure. We therefore consider utilization of the hydrogen in the vehicle fuel cell and dissipation of the electricity by operating vehicle accessories or electric resistances as an alternative to releasing hydrogen to the environment. We consider two strategies: initiating hydrogen extraction immediately after vacuum insulation failure or waiting until maximum operating pressure is reached before extraction. The results indicate that cryogenic pressure vessels have thermodynamic advantages that enable slowing down hydrogen release to moderate levels that can be consumed in the fuel cell and dissipated in vehicle accessories supplemented by electric resistances, even in the worst case when the insulation fails at the moment when the vessel stores hydrogen near its maximum density (70 g/L at 300 bar). The two proposed strategies are therefore feasible, and the best alternative can be chosen based on economic and/or implementation constraints.

Introduction

Hydrogen is considered a strong candidate to replace hydrocarbons as transportation fuel, with the advantage of eliminating environmental pollution during both production and utilization. Its physical and chemical properties make it superior to fossil fuels, because it has the capability of generating clean and efficient energy while producing only water and no CO_2. However, its main disadvantage is its low energy density compared to hydrocarbons, thus its widespread use has been limited [1].

The concept of using hydrogen as a substitute for hydrocarbons is not new, however in comparison to hydrocarbons,

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hydrogen storage and delivery are challenging. Hydrogen has low density, occupying in liquid state (saturated at 20.2 K and 1 bar) about four times more volume per unit of energy than gasoline [1]. The storage method will be determined by the final application and must have a competitive cost [2]. The two most viable options from technical (in which safety plays a key role) and economical points of view are hydrogen storage as liquid and as compressed gas [3,4].

Liquid hydrogen is most widely used for large-scale storage. In vehicles, however, compressed gas currently dominates even though it requires expensive high-pressure containers. Liquid hydrogen is much denser (up to 70 gH_2/L vs. ~40 gH_2/L for compressed gas), potentially leading to lower distribution and onboard storage cost in automobiles [1]. However, hydrogen losses during periods of inactivity have limited its use. Liquid hydrogen vessels are typically built for low pressures, with ~5 bar maximum allowable working pressure (MAWP). In pressure vessels, MAWP is the relief device setting, where the hydrogen needs to be released to avoid overpressurization. At 5 bar MAWP, short periods of inactivity (2–3 days) pressurize the vessel enough to demand hydrogen release, even for very well insulated vessels (1–3 W/m^2).

An alternative has recently arisen: cryogenic pressure vessels that can operate at high pressure [5–9]. Also known as cryo-compressed vessels, they consist of a high-pressure (300–700 bar MAWP) metal lined, fiber-wrapped (type 3) inner vessel, a vacuum space containing numerous sheets of highly reflective metalized plastic, and an outer metallic jacket (Fig. 1). Cryogenic pressure vessels enable substantial reduction or elimination of fuel losses resulting from hydrogen pressurization beyond the vessel MAWP as a consequence of heat transfer from the environment, because (1) heat transfer from the environment is reduced to very low values (1–3 W/m^2) due to the vacuum insulation simultaneously reducing all heat transfer mechanisms (conduction, convection and radiation), (2) the vessel is filled with liquid or cryogenic pressurized gaseous hydrogen, both of which have very low entropy, minimizing heating during the fill process, and (3) hydrogen is typically extracted from the vessel at higher temperature and entropy, thus extraction results in considerable cooling and depressurization of the hydrogen stored in the vessel. The proposed vessels have successfully completed a series of certification tests through three generations of prototypes [5–7].

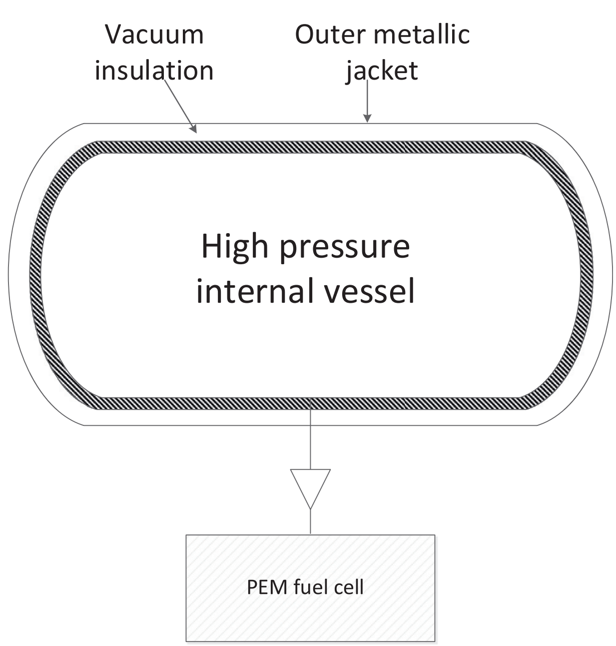

Fig. 1 – Schematic of cryogenic pressurized hydrogen storage system.

Cryogenic pressure vessels enable storage of high-density (70 g/L) cryogenic hydrogen without the boil-off losses typical of liquid hydrogen vessels. As a direct consequence of storing high density H_2, cryogenic pressure vessels are compact and cost effective, decreasing cost by reducing the amount of expensive materials (composite and metal) necessary for manufacture. Cryogenic pressure vessels are therefore predicted to be less expensive than competing technologies. Low vessel capital cost combined with cost effective liquid hydrogen delivery and pressurization at the station result in the lowest cost of ownership of all available hydrogen storage technologies [10].

Cryogenic pressure vessels also present attractive safety advantages [11–14]. Several studies have analyzed the sudden expansion and release of hydrogen subsequent to vessel failure [15–17], and it has been demonstrated that expansion energy is significantly reduced due to operation at cryogenic temperature, even though storage pressure is high. The vacuum jacket reduces venting pressure by one order of magnitude, and other parameters such as energy release rate and thrust are considerably lower than in compressed gas vessels [16,18–21]. Other researchers have developed models to analyze the dispersion of hydrogen when released at cryogenic conditions [22,23] and its potential ignition [24], where the maximum ignition distance is a key parameter for safety codes and standards for hydrogen infrastructure.

In this work, we consider a previously unexplored safety aspect of cryogenic pressure vessels: the failure or leakage of the outer metallic jacket with the consequent loss of vacuum and sudden increase (~100×) in heat transfer from the environment. Under these conditions, it is possible that a fraction of the hydrogen may need to be released to the environment to avoid exceeding the MAWP. Hydrogen release introduces the danger of ignition, and the danger increases if release occurs when the vehicle is in an enclosed space (e.g., a garage or tunnel) [25–27].

A safer alternative to releasing hydrogen to the environment is *consuming* the extracted hydrogen. Depending on the extraction rate, it might be possible to consume the hydrogen in the vehicle fuel cell and dissipate the electricity generated by operating the vehicle accessories (mainly air conditioning). It is therefore critical to calculate the rate at which hydrogen needs to be extracted from the cryogenic pressure vessel and the electric power generated to determine if it is possible to (1) consume the hydrogen in the fuel cell, and (2) consume the electricity generated by the fuel cell in the vehicle accessories, possibly aided by electric resistances.

We calculate the hydrogen extraction rate according to two different strategies: (1) Initiate hydrogen extraction immediately upon vacuum vessel failure. This strategy minimizes hydrogen extraction rate but demands vacuum sensors or