

On-Board Physical Based 70 MPa Hydrogen Storage Systems

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ABSTRACT

Fossil energy diversity and security along with environmental emission policies demand new energy carriers and associated technologies in the future. One of the major challenges of the automotive industry and research institutes worldwide currently is to develop and realize alternative fuel concepts for passenger cars. In line with Ford's global hydrogen vehicle program, different onboard hydrogen storage technologies are under investigation. In general, hydrogen storage methods can be categorized as either physical storage of hydrogen (i.e. compressed, liquid, or cryo-compressed) or material based hydrogen storage. Currently, automotive OEMs have only introduced hydrogen fleet vehicles that utilize physical-based hydrogen storage systems but they have recognized that hydrogen storage systems need to advance further to achieve the range associated with today's gasoline vehicle.

At Ford Motor Company, compressed gaseous hydrogen storage systems at 35 MPa (350 bar) have been deployed to a fleet of hydrogen fuel cell vehicles as well as internal combustion engine powered vehicles. The direct customer feedback from these hydrogen fleet vehicles was the need for improved driving range to be comparable with conventional vehicles. Through doubling the working pressure to 70 MPa (700 bar), the volumetric storage density of the fuel storage system significantly improves closing the performance gap of driving range. In this report, next-generation 70 MPa hydrogen storage systems are presented with regard to their overall design, component development, refueling capabilities, and verification testing on component, system as well as vehicle level. Overall, the 70 MPa hydrogen storage systems have demonstrated significant improvement in the compressed hydrogen fuel capacity facilitating the path for achieving greater than 300 miles range on fuel cell vehicles.

The Ford 70 MPa hydrogen storage systems have been developed using the internal product development disciplines and have achieved the implementation milestone. The 70 MPa system designs were based on today's state-of-the-art hydrogen storage technology and have proven to provide the desired functionality and appropriate safety in particular with regard to certification and approval according to North America standards as well as European regulations.

INTRODUCTION

On-board hydrogen storage is one of the key enablers to progress the transportation sector toward a hydrogen economy. There are many reasons that make hydrogen attractive as a fuel for automobiles such as: improved fuel efficiency, reduced or zero emissions, environmental benefits, and opportunities for domestic and renewable energy sources. Despite these benefits, one of the outstanding challenges for hydrogen vehicles to be competitive with their gasoline counterparts is driving range. This challenge is associated with the significant volume required for the hydrogen fuel system. The initial implementation of hydrogen vehicles utilized compressed hydrogen stored at 35 MPa based on the natural progression from compressed natural gas at 25 MPa. Even with the improved efficiency of a fuel cell vehicle (50 to 60 mpgge), the typical range for the majority of the initial hydrogen vehicles were limited to 200 miles which is significantly below the typical US market data for conventional vehicles as shown in the figure below [1].

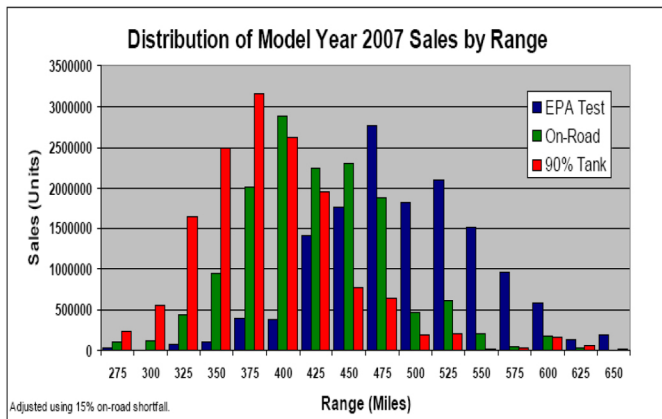


Figure 1. Conventional Vehicle Driving Range in the 2007 US Market based on Sales Volume

targets for volumetric and gravimetric density are along with the progression to the ultimate target although the complete target list [1] contains a total of 24 system parameters (including safety, performance, efficiency, and cost). The focus of this paper is to examine the progress and potential of physical based 70 MPa hydrogen storage systems to satisfy customers with a commercially viable fuel system to progress towards the hydrogen economy.

Table 1. FreedomCAR Hydrogen Storage System Targets for Light-Duty Vehicles

Target	2010	2015	Ultimate
System Gravimetric Density	4.5 % (1.5 kWh/kg)	5.5% (1.8 kWh/kg)	7.5% (2.5 kWh/kg)
System Volumetric Density	28 g/l (.9 kWh/l)	40 g/l (1.3 kWh/l)	70 g/l (2.3 kWh/L)

PROPERTIES OF HYDROGEN

Hydrogen is the most abundant element, comprising about three quarters of the mass in the Universe. It is found in water that covers 70% of the earth's surface and also in all organic matter. Hydrogen is the lightest of all elements; in a gaseous state it diffuses immediately upwards into the air and does not pollute the ground or groundwater. It is colorless, odorless, and nontoxic. Hydrogen does not produce acid rain neither depletes the ozone or produces harmful emissions. The gravimetric energy density of hydrogen (33.3 kWh/kg) is approximately three times the gravimetric energy density of gasoline (12.7 kWh/kg). However, the low volumetric energy density of hydrogen (0.77 kWh/l at 35 MPa and 300 K) in comparison to gasoline (8.76 kWh/l) is the reason for the increased package volume required for a hydrogen storage system compared to conventional gasoline/diesel fuel systems.

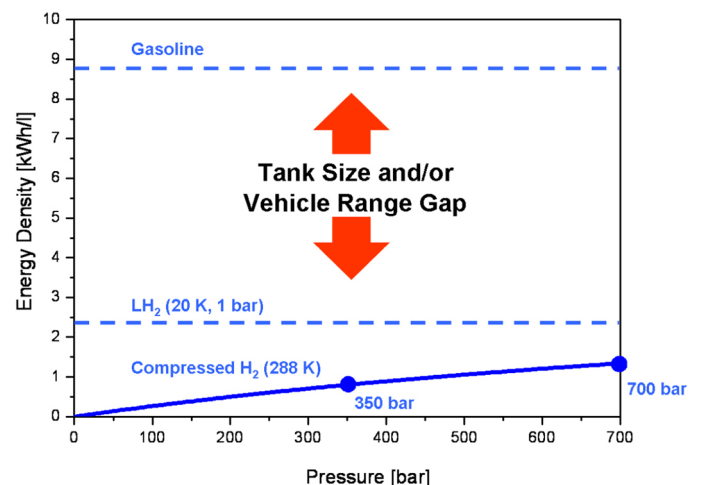


Figure 2. Volumetric energy density of hydrogen (compressed gaseous and liquid) compared to gasoline

The fuel capacity of a hydrogen storage system obviously depends on the total tank volume, the maximum storage pressure, and the temperature of the gas stored. Nevertheless, since hydrogen does not show an ideal gas behavior but rather a real gas behavior there is no linear correlation between hydrogen density and gas pressure. Hence, the amount of hydrogen stored at various conditions needs to be calculated on the basis of an appropriate equation of state, e.g. the Redlich-Kwong equation of state, as shown below:

Redlich-Kwong equation of state [3]:

$$p = \frac{RT}{V-b} - \frac{a}{\sqrt{TV}(V+b)}$$

empirical constant: $a = 0.42748 R^2 T_c^{2.5} / p_c$

empirical constant: $b = 0.08664 RT_c / p_c$

ideal gas constant: $R = 8.31451 \text{ J/mol K}$

critical pressure of hydrogen: $p_c = 1.316 \cdot 10^6 \text{ Pa}$ [4]

critical temperature of hydrogen: $T_c = 32.23 \text{ K}$ [4]

pressure (Pa): p

molar volume (m^3/mole): V

temperature (K): T

Figure 3 shows a comparison of data calculated by the ideal gas law as well as with the Redlich-Kwong equation of state with experimental data valid for hydrogen at 300 K. Although the ideal gas law data correlates well with the experimental data at low gas pressures below 10 MPa, it exhibits a large error at 70 MPa of approximately 44 %. However, the Redlich-Kwong equation of state shows a good correlation with the experimental data. At a gas pressure of 70 MPa, it exhibits an error of approximately 1% compared to the experimental data. Below 70 MPa the error decreases.

The nominal working pressure is the gauge pressure that characterizes operation pressure of the system. For compressed hydrogen, the rated volumetric density is specified by the industry at the nominal working pressure according to a uniform gas temperature of 15 °C (NOTE: nominal working pressure is also called Service Pressure). At a gas temperature of 15 °C, the density of hydrogen improves by 67% when increasing the nominal working pressure from 35 MPa (24 g/l) to 70 MPa (40 g/l).

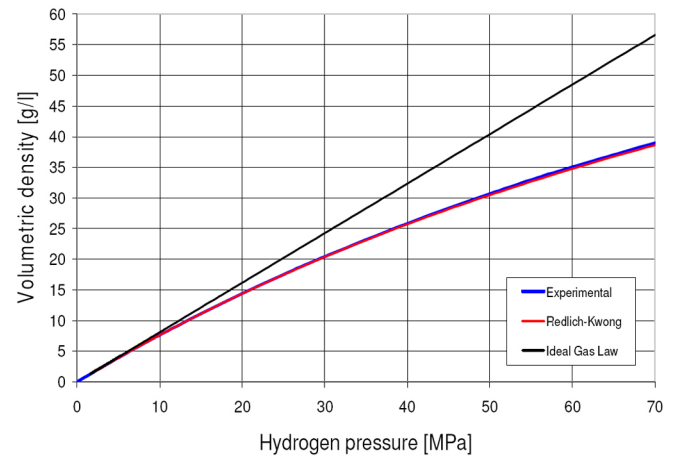


Figure 3. Volumetric density of hydrogen at 300 K as a function of pressure, experimental data [4]

CHALLENGES OF HYDROGEN

In comparison to other fuels, hydrogen has unique properties that create challenges for a fuel storage system. In particular, hydrogen gas molecules are smaller than other gas molecules, which contributes to the difficulty in containing hydrogen at interface connections and the diffusion through materials. As with any fuel, managing leaks is important and often emphasized with hydrogen due to the wide range of flammability (4% to 74%) and low ignition energy (0.02 mJ at 30%) in air. The diffusion effects of hydrogen can cause an acceleration of formation of fatigue cracks in metal, known as hydrogen embrittlement. As the nominal working pressure is increased to 70 MPa, the challenges of hydrogen are further magnified. As an example, pressure and stress ratios are known factors that can influence the severity of hydrogen embrittlement. Another effect of higher storage pressure is the temperature changes within the storage system due to compression and decompression. In fact, the heat of compression for 70 MPa requires pre-cooling (industry has identified a preference of -40°C) during fueling. The increase in pressure, temperature effects (pre-cooling due to the heat of compression to 85°C), and embrittlement results in further attention required in the sealing designs, material selection, and operation protocols.

HYDROGEN STORAGE SYSTEM OVERVIEW

This section provides a summary of the three different on-board 70 MPa hydrogen storage systems developed for Ford vehicles, including an overview of the fuel system package as well as the attribute comparison for each fuel system.