VI.E Compressed/Liquid Tanks

VI.E.1 Low Cost, High Efficiency, High Pressure Hydrogen Storage

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Objectives

Design and develop a low-cost on-board hydrogen storage system to achieve 2010 DOE storage targets.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Cost
- B. Weight and Volume
- H. Sufficient Fuel Storage for Acceptable Vehicle Range
- I. Materials

Technical Targets

There are three primary technical targets that Quantum has focused its efforts on – specific energy, energy density, and system cost. The other technical targets are achievable using Quantum's compressed hydrogen technology.

Storage Parameter	Units	2007 Targets	2010 Targets	Current 10,000 psi System Status
Specific Energy	kWh/kg	1.5	2.0	1.3
Energy Density	kWh/L	1.2	1.5	0.8
Storage System Cost	$/kWh	6	4	10

Approach

Quantum will be using 10,000-psi compressed hydrogen storage tanks to achieve the DOE hydrogen storage technical targets. Techniques to be explored include:

- Composite design and process optimization to improve weight efficiency and reduce material usage,
- Embedding sensors to monitor cylinder health and reduce over-design requirements (resulting in lower weight and cost), and
- Cooling hydrogen to increase storage density.

The goal in Phase I of the project is to produce development tanks that reduce the amount of composite materials required without sacrificing safety through design and process optimization. Since the tank is a significant portion of the system weight, the optimization efforts will also improve system level efficiency.

Accomplishments

- Successfully employed low-cost, commercial grade carbon fiber to fabricate 10,000 psi storage tanks with the same level of performance as tanks using aerospace grade carbon fiber.
- Identified strain signatures for healthy and damaged tanks under cyclic loading. This information will be used to monitor the state of the tank during service and help determine if the tank is no longer safe for use.
- Completed finite element analysis (FEA) model of composite tank for predicting thermal behavior during gas charge and discharge. Verified FEA model through test data.

Future Directions

- Improve the manufacturing process for the localized reinforcement concept through fiber placement and evaluate the efficacy of the approach. Perform vehicle level testing with the storage system to verify design robustness.
- Complete evaluation of sensor integration using analog and optical sensors.
- Continue investigation into on-board storage of hydrogen gas at low temperatures through passive cooling methods. Study will include an assumed fill/discharge cycle.
- Explore methods of off-board hydrogen delivery at low temperatures, including rejection of heat during refueling.

Introduction

There is a strong demand in the automotive market for cost-effective and efficient high-pressure hydrogen storage systems. The world's premier automotive original equipment manufacturers that are developing fuel cell vehicles have demonstrated significant interest in this technology. The current Quantum TriShield™ tank technology is close to meeting the percent weight, energy density, and specific energy goals of 6% hydrogen by weight. However, the current product line utilizes premium aerospace-grade carbon fiber reinforcement to meet the challenging structural requirement of supporting over 23,500 psi burst pressure as specified in current regulations. It is unreasonable to expect a significant carbon fiber cost reduction to achieve the cost goal of $5 per kW-h, even if economies of scale are taken into account.

Approach

The primary focus is to meet the cost goal of the DOE hydrogen storage technical targets. Quantum's current 10,000-psi TriShield™ tank technology is close to meeting many of DOE's targets, but cost is still a major issue. Since the carbon fiber cost is a large portion of the overall cost, the approach is to reduce the amount of carbon fiber needed to build the storage system while maintaining equivalent levels of performance and safety. This will be accomplished by improving the fiber translation using non-conventional filament winding processes and integrating sensors to actively monitor tank health. Reducing the amount of fiber used will also reduce the overall weight of the system. In addition, a third track to this project involves reducing the temperature of the stored hydrogen in order to increase its density.

Results

The first 10,000 psi hydrogen storage tank designs developed by Quantum, with DOE funding, utilized high grade aerospace fiber to attain high performance. This achievement came at a very high cost due to the premium carbon fiber used. Subsequent 10,000 psi designs were able to employ mid-grade aerospace fibers, but the costs were still too high for commercial applications. The effort in Track 1 resulted in a 10,000 psi design using commercial grade carbon fiber while maintaining the level of performance on other technical goals. Using subscale tanks, the specific energy for the baseline system design (mid-grade aerospace carbon fiber) is about 0.66 kw-hr/kg, which equates to approximately 1.3 kw-hr/kg at full scale. Quantum designed, fabricated, and tested over 20 tanks using various fiber types and resin systems in an effort to meet or exceed this baseline value. Through composite design and wind pattern optimization, 1 subscale design using commercial grade fiber was able to achieve 0.68 kw-hr/kg. However, this process alone will not produce a storage system that exceeds the 1.5 kw-hr/kg goal for 2007 (see Figure 1).

Another approach Quantum is investigating is lowering the safety factor of the tank design while increasing the safety level of the storage system through the integration of strain sensors. Measuring increased localized strain resulting from structural damage to the pressure vessel may provide for the ability to reduce the design safety factor, thus reducing the amount of required carbon fiber. The focus of implementing this strategy has been several-fold: First, the type of sensors used to measure strain must meet certain criteria; second, the number of sensors must be adequate for measuring strain anywhere on the vessel and must be compatible with manufacturing methods; and third, the cost of sensors must be low enough to decrease the cost of the overall system.

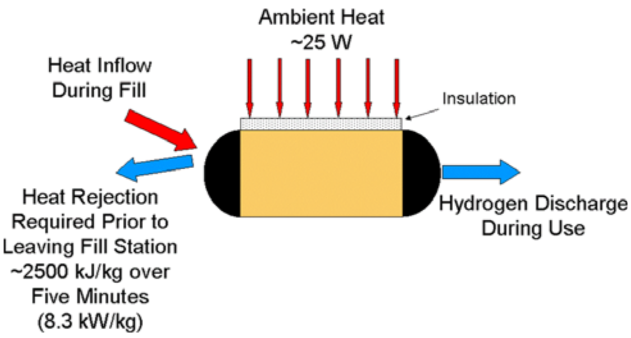

Figure 1. Composite Optimization Results

The current sensors under investigation are analog strain sensors and fiber optic strain sensors. The advantages of analog strain sensors are low-cost and have a longer history of success in a variety of applications. The disadvantages of using analog sensors are that they require point-to-point wiring, and tend to be less robust when used in fatigue applications such as called for by this project. Fiber optic sensors have the disadvantages of being high cost and easily damaged during tank manufacture, but the advantages are that many of them can be applied with a single connection and they are well suited for fatigue cycling applications. In the long run, the cost of fiber optics is expected to fall markedly, further improving their applicability.

The sensors themselves have provided sources of measurement error in the tests to date. The analog strain sensors are not well adapted to fatigue cycling while attached to a polymer surface as in these tests. As a result, the analog sensors tend to become saturated early in the cycling tests and thus fail to provide useful information. On the other hand, the optical strain sensors last through the cycling, but tend to exhibit confounded signals when placed in transient strain. The strain sensors produce a peak value which represents the maximum strain, and as the pressure increases to the maximum value, the strain peak tends to split to produce two different values. The difficult task here is to have software that can accurately choose the correct peak value to measure each time the peaks split, which is not consistent, or manufacture a method to eliminate transverse loads.

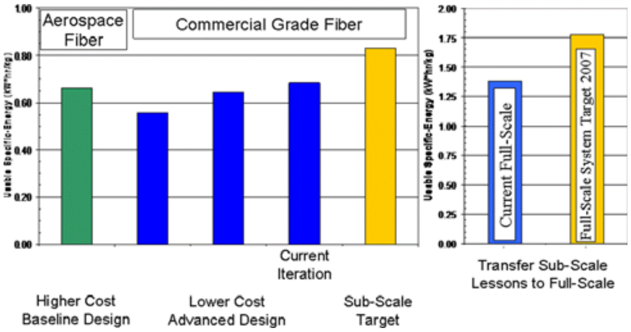

Figure 2. Estimated System Energy Balance

Work performed for the third track of this project, called CoolFuel™, has resulted in a thermal FEA model that allows for the simulation of charging and discharging of a pressure vessel, estimated values for heat rejection requirements for an off-board refueler, and direction for the implementation of the on-board passive temperature stabilization system. An FEA model has been completed and validated against experimental results. With this model, simulations may be completed before prototypes are built. The heat rejection necessary for gaseous charging of a 160 liter pressure vessel will require a heat transfer system built into the off-board refueler. The on-board temperature stability system will consist of a light-weight passive insulation system as opposed to an active system that would increase the system weight and power requirements. The insulation system will utilize state-of-the-art materials and methods to reduce the heat flux to the system while occupying little volume. The energy balance for the system, based on a preliminary analysis, is shown in Figure 2.

Conclusions

Design optimization through conventional means has the potential to yield a specific energy of approximately 1.5 kW-hr/kg. However, it will require unconventional means such as localized reinforcement to exceed this value. Quantum will employ fiber placement techniques to achieve these goals.

Despite many challenges, the use of active sensors to monitor the storage system health remains an attractive approach. Quantum has demonstrated that the tank design has a strain signature for a healthy tank while damaged tanks will deviate from this signature. If the sensor array required to monitor the entire tank is economical enough at a sufficient level of robustness, then this system would not only reduce the weight and cost of the tank design, but also act as an active safety feature. For example, a refueling station could "check" with the sensors before every fill to make sure that the tank is safe for use. The potential advantages of this sensor system are tremendous because Quantum estimates that the specific energy can reach as much as 1.75 kw-hr/kg due to the significant amount of carbon fiber removed by reducing the over-design margin. The downside of this approach is the high cost of the sensor system, which results in an estimated $17/kw-hr.

The two approaches described should have little correlation in terms of performance results so preliminary estimates show that the cost metric can be reduced to $10/kw-hr and it is possible that the specific energy can reach above 1.75 kw-hr/kg by combining the efforts of the two tracks.

The preliminary analysis performed on the CoolFuel™ concept shows some promise but further detailed analysis is necessary before drawing any conclusions on this approach.