Advanced Thermal Hydrogen Compression

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Objectives

- Develop a hydride thermal hydrogen compressor that operates in conjunction with advanced hydrogen production technologies and improves the efficiency and economics of the compression process.
- Construct and test a single-stage thermal compressor that employs miniature hydride heat exchangers and three purification technologies to determine threshold contamination levels (levels at which compressor performance is affected) for H_2O, O_2, CO, CO_2 and CH_4.
- Investigate compressor capabilities to perform the dual function of compression and purification for impurities that adversely affect fuel cell operation (CO and CH_4).
- Engineer and test hydride alloys suitable for long-term operation at high pressures over 5,000 psig.
- Validate the entire compressor process in a multi-stage, pilot-scale system.

Technical Barriers

This project addresses the following technical barriers from the following sections of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

<u>Hydrogen Delivery</u>

- B. High Costs of Hydrogen Compression

<u>Hydrogen Storage</u>

- S. Cost
- T. Efficiency

Approach

- Feasibility
  - Quantify H_2 quality anticipated from renewable production techniques.
  - Conduct preliminary design and safety analysis.
- Validate and Test
  - Determine hydride alloys' resistance to disproportionation.
  - Validate compressor operation to >5,000 psi.
  - Determine hydride alloys' tolerance to impurities while cycling.
  - Test effectiveness of three purification techniques (passive purification for H_2O & O_2, elevated temperature desorption for CO & CO_2, inert gas venting for N_2 & CH_4).

- Refine Product Design
  - Determine if compression with purification is a viable alternative for improving fuel cell performance.
  - Reduce capital cost via miniature hydride heat exchangers and rapid cycling.

Accomplishments

- Determined that hydride compression's low energy cost will substantially reduce the cost of high-pressure hydrogen.
- Demonstrated thermal compression to 8,000 psia with a clear path to 10,000 psia.
- Reduced hydrogen CO content from 300 ppm to less than 10 ppm to protect fuel cell catalyst.

Future Directions

- Determine upper limits and removal efficiencies for contaminants that might damage either fuel cells or advanced storage media.
- Refine product design.
- Demonstrate full-scale hydride thermal compression at a hydrogen refueling station.

Introduction

The hydride thermal compressor is an absorption-based system that uses the properties of reversible metal hydride alloys to silently and cleanly compress hydrogen; hydrogen is absorbed into an alloy bed at ambient temperature and, subsequently, is released at elevated pressure when the bed is heated. Compression energy can be supplied by hot water and, for the very high pressures being considered for on-board hydrogen storage, is a fraction of the energy cost of mechanical compression. The primary technical objective of this project is to determine whether hydride compressors can be used for non-pure hydrogen streams likely to result from advanced hydrogen production methods (i.e. from renewable resources), with the commercial objective of developing a viable hydride compressor that offers substantial benefits over mechanical compressors.

A pilot-scale hydride thermal compressor was built and is being tested to determine the extent to which a hydride compressor can both tolerate and remove impurities from the hydrogen stream. In particular, CO is present in hydrogen from many advanced production processes and must be removed to prevent damage to fuel cell electrode catalyst. Removing CO in the compression process can be more cost effective than other hydrogen purification schemes. A novel process has been developed that reduces carbon monoxide levels to less than 10 ppm. In addition, the compressor employs miniature hydride heat exchangers to reduce capital cost and has operated to pressures in excess of 8,000 psia.

Approach

Advanced Thermal Hydrogen Compression is a comprehensive project with three phases: feasibility, validation and test, and product refinement. A full-scale demonstration at a hydrogen refueling station is anticipated following the completion of the current project.

In the feasibility phase of the project, Ergenics, Inc. investigated the application of thermal hydrogen compression to hydrogen produced from renewable resources and developed a preliminary thermal compressor design for comparison with conventional mechanical compressors. A hazardous operation safety analysis of the thermal compressor system was completed. Thermal hydrogen compression was found to have distinct operational and economic advantages over mechanical compression for a majority of advanced hydrogen production processes.

In the validation and test phase of the project, a pilot-scale compressor and test stand were built and are being operated to determine the extent to which a hydride compressor can both tolerate and remove impurities from the hydrogen stream. While testing is on-going, excellent results have been achieved and are reported below.

Product refinement has included the demonstration of hydride compression to 8,000 psia with a clear path to 10,000 psia. In addition, complexity and cost of the compression process have been reduced through the identification of disproportionation resistant hydride alloys [1]. A competitive analysis of compressor efficiency and fuel costs for operation at 5,000 and 10,000 psia indicates that hydride compression has eight times lower energy cost than mechanical compression, which will be necessary to meet the hydrogen delivery cost goals of $3.00 per gallon of gasoline equivalent by 2004 and $1.50 per gallon of gasoline equivalent by 2010.

Results

Effect of CO on Alloy Capacity. Ergenics developed and demonstrated a novel CO elimination process that allows the hydride compressor to tolerate and remove CO from the hydrogen stream. Figures 1 and 2 show the effect of CO on alloy capacity with cycling. Figure 1 shows that hydride alloy capacity undergoes a gradual reduction with cycling when hydrogen with CO is fed to the compressor without the CO elimination feature. If left alone, compressor performance would rapidly degrade. The positive impact of the novel CO elimination process is shown in Figure 2, where alloy capacity remains stable as the alloy is cycled.

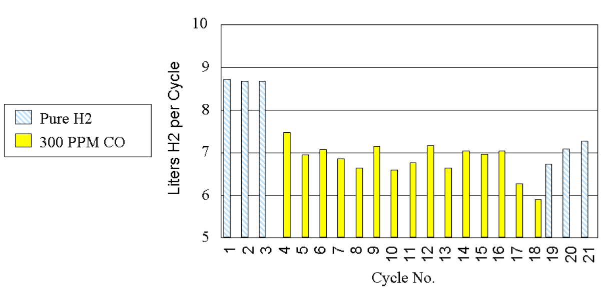

Figure 1. When 300 ppm CO Is Added to Feed Hydrogen, Alloy Capacity Gradually

During testing with CO, the compressor alloy behavior was periodically checked for changes by pressure-composition-temperature (PCT) isotherm tests. Figure 3 shows that the CO elimination feature allows the compressor alloy to maintain its performance over repeated cycles. In order to verify that the PCT performance was not being affected by potential test stand leakage, two additional absorption tests, numbers 3 and 4, were done after 10 cycles. The results conform to the isotherm of "Abs. 2" and have been omitted from Figure 3 for clarity. The slight differences in plateau pressure are a result of ambient temperature differences on the days the tests were performed.

CO Elimination. The composition of the compressor discharge with the CO elimination feature is depicted in Figure 4. The CO elimination process results in a reduction of CO from 300 ppm at

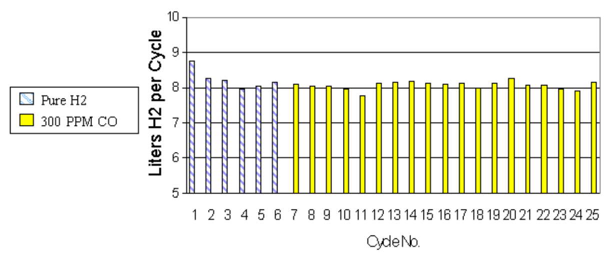

Figure 2. The CO Elimination Feature Maintains Alloy Capacity at a Constant Level

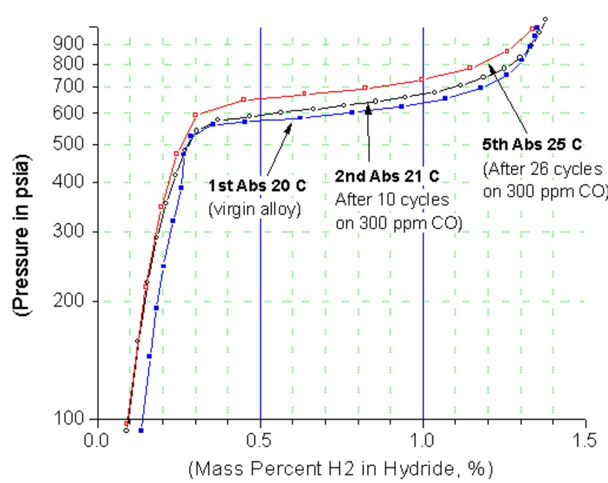

Figure 3. PCT Tests Indicate the Hydride Alloy Is Not Damaged During Testing with CO

the compressor inlet to the 10 ppm level necessary to protect fuel cell catalyst. Figure 4 illustrates that most of the CO is converted into methane (CH_4) and the methane is released in large spikes (>1,000 ppm) at the beginning of each cycle. This suggests that methane can be removed from the hydrogen stream via inert gas venting using an economically small amount of hydrogen. A momentary opening of the vent valve will sweep the methane away. Ultimately, the vent gas will be routed to the hot water heater for recapture of its heating value.

Very High Pressure. The compression capability of the advanced hydride compressor is presented in Figure 5, which plots inlet and outlet hydrogen pressure and inlet water temperature vs time for one compression cycle. Compressed hydrogen is vented via a back-pressure regulator. For this test, the regulator was set at 8,200 psia (56 MPa). The slight fluctuation in water temperature is associated with the natural gas heater cycling on and off and, interestingly, causes a slight, but detectable, fluctuation in hydrogen pressure.

The test stand uses an ethylene glycol-water mixture for the heat transfer fluid, which has an upper temperature limit of 175°C to prevent boiling. Substituting the ethylene glycol-water mixture with a silicone-based heat transfer fluid will permit operation to 200°C with pressures over 10,000 psia.

Energy Cost and its Effect on the Delivered Cost of Hydrogen. The hydride thermal compressor is a form of "heat engine" based on the Carnot thermodynamic cycle [2]. Its energy efficiency is based on the temperature difference between a hot energy source and a cold heat sink (i.e. hot water and cooling water), with efficiency increasing with a larger difference in temperature.

By using a traditional form of heat energy, such as natural gas, cycle economics benefit from an increase in hot water temperature. Using a heat transfer fluid from a gas-fired heater at 130°C and 30°C cooling water, hydride compressor efficiency is approximately 15 percent. While 15 percent is about 1/2 that for an electric-motor-driven mechanical compressor operating around 3,000 psia, electricity is about 6 times costlier than natural gas, so the hydride compressor will enjoy a 67% lower energy cost.

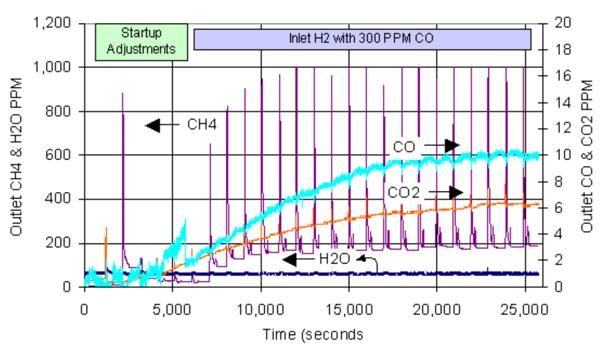

Figure 4. The CO Elimination Feature Reduces Outlet CO Concentration from 300 to 10 ppm

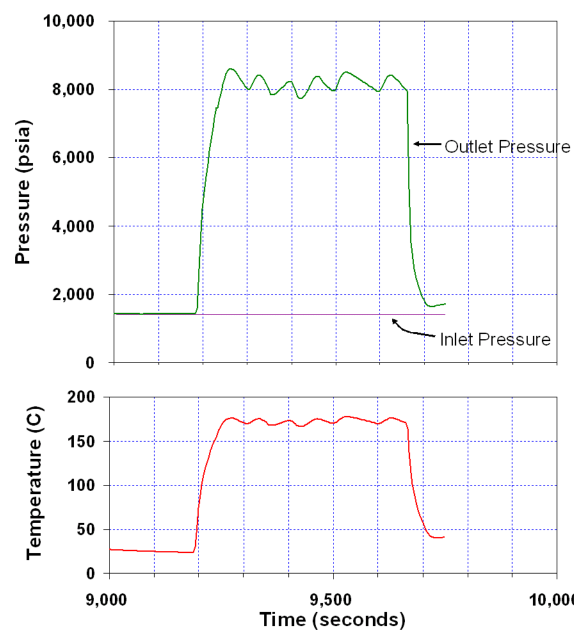

Figure 5. Testing to 8,000 psia

H_2 Quantity	1 kg		1 kg	
Inlet Pressure	15 psia		15 psia	
Outlet Pressure	5,000 psia		10,000 psia	
Adiabatic Work	1,960 watt hours = 6,690 BTU		2,194 watt hours = 7,485 BTU	
Compressor Type	Mechanical	Hydride	Mechanical	Hydride
Efficiency	12%	15%	6%	10%
Fuel	Electricity at $0.05 / kWh	Natural Gas at $3 / MM BTU	Electricity at $0.05 / kWh	Natural Gas at $3 / MM BTU
Comp. Energy Cost / kg H_2	$0.82	$0.14	$1.83	$0.23
Energy Cost / H_2 Cost at $3.00/gge (2004)*	27%	5%	NA	NA
Energy Cost / H_2 Cost at $1.50/gge (2010)*	55%	9%	122%	15%

Figure 6. Hydride Thermal Compression's Low Energy Cost Will Substantially Reduce the Cost of Hydrogen

The energy cost savings are magnified at the high pressures being looked at for the first generation of hydrogen vehicles. Mechanical compressor efficiencies decline to a range of 8% to 12% at 5,000 psia and only 4% to 6% at 10,000 psia. Hydride compression efficiencies remain in the 15% and 10% range, respectively. A table relating compression energy cost as a function of the DOE hydrogen cost targets is presented in Figure 6. Hydride compression reduces energy cost from 5 to 8 times.

Conclusions

The hydride thermal hydrogen compressor demonstrated high compression, tolerance to impurities, and the ability to both compress and purify hydrogen. An energy cost analysis shows hydride compression substantially reduces the delivered price of high-pressure hydrogen.

Advanced thermal hydrogen compression directly supports the technical targets established in the Department of Energy's Multi-Year Research, Development and Demonstration Plan as follows:

- **H_2 Cost:** Reduce compression energy costs by up to an order of magnitude to meet the H_2 cost goals of:
  - Long Term: $1.50/gallon of gasoline equivalent (2010)
  - Near Term: $3.00/gallon of gasoline equivalent (2004)
- **Energy Density:** Demonstrate pressures of 5,000 and 10,000 psi to support high pressure tank development.
- **H_2 Purity:** Increase H_2 quality to protect both fuel cell catalyst and advanced hydrogen storage materials (<10 ppm CO).
- **Complex/Carbon Materials:** Knowledge of impurity effects on compressor hydrides will establish a baseline for understanding impurity impact on advanced storage materials (alanates & carbon nanomaterials).

References

1. D. DaCosta, M. Golben. "Disproportionation Resistant Alloy Development for Hydride Hydrogen Compression", Proceedings 2002 U.S. Department of Energy Hydrogen Program Annual Review Meeting, Golden, May 6-8, 2002, NREL/CP-610-32405.

2. D. DaCosta, M. Golben, D.C. Tragna. "Metal Hydride Thermal Hydrogen Compression", Proceedings 14th World Hydrogen Energy Conference, Montreal, June 9-13, 2002.

FY 2003 Publications/Presentations

1. D. DaCosta, M. Golben. "Thermal Hydrogen Compression with Purification", International Energy Agency Hydrogen Implementing Agreement, Task 17 - Solid and Liquid State Hydrogen Storage Materials Workshop, Geneva, Switzerland, September 9-11, 2002.