VI.B.1 Novel Compression and Fueling Apparatus to Meet Hydrogen Vehicle Range Requirements

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Objectives

- Develop components for 700 barg hydrogen fueling.
- Develop and optimize a new compression process that is lower in cost, maintenance, and power consumption.
- Test the technology in a laboratory setting and potentially at a field site.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.5.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(C) Hydrogen Refueling Infrastructure

Technical Targets

Milestone 6: Validate vehicle refueling time of 5 minutes or less. We are demonstrating a new technology compressor and system components capable of operation at 972 barg, the required overpressure for cascade fueling (most common method used to achieve fast fills) at 700 barg.

Milestone 14: Validate $2.50/gge hydrogen cost. We are demonstrating a new technology compressor with lower cost, maintenance, and power usage. We expect a savings of up to 70% over existing technologies, when mass produced.

Accomplishments

- Tested newly developed valves and other components in fueling service at three 700 barg hydrogen fueling systems (two domestic, one in Asia) using conventional compression technology.
- Developed a dual-pressure dispenser with both 350 and 700 barg in a single enclosure.
- Developed a new single-stage compressor system with: ~50°F temperature rise, a compression ratio of 140:1, no gas seals to the atmosphere, no exotic materials or complicated machining required, and a small footprint (3'x4'x7').
- Reduced compressor cycle time from 30 to 10 seconds, increased compressor flow rate from 1 to 5 nm^3/hr, and removed one eductor with a net reduction in system cost.
- Identified a potential problem with previously selected fluid reacting exothermically with hydrogen.
- Selected and tested a new suitable fluid for the isothermal compressor.
- Completed assembly of isothermal compressor prototype.
- Pressure tested isothermal compressor prototype.
- Initiated laboratory testing of isothermal compressor prototype.

Introduction

One of the technical barriers encountered by today's automakers is providing hydrogen-powered vehicles that have a range comparable to vehicles fueled by gasoline.

Onboard hydrogen storage at 700 barg as opposed to 350 barg appears to be one good solution. These vehicles will require fueling stations with storage at 972 barg (14,100 psig) to achieve fast fills (4-6 minutes). To make this a reality, all of the system components used in the refueling process must be upgraded to accommodate the higher pressure. Compressors capable of generating higher pressures, and valves, instruments, dispensers and storage vessels with the ability to handle those pressures are needed.

Air Products has worked with its vendors to develop and test many of the components necessary for 700 barg fueling, including pressure transmitters and other instruments, fueling hoses, breakaways, and nozzles. Traditional technology is available to compress hydrogen up to 972 barg, but is extremely expensive and not efficient.

The primary goal of this project is to develop a new compression technology that would exhibit lower cost, maintenance, and power usage than today's compressors. We have developed a compression process that relies on a liquid compression cylinder to eliminate many of the problems associated with today's high-pressure hydrogen compressors, which require gas seals. A process flow diagram for this novel compression technology is shown in Figure 1.

Approach

Our design approach was to first determine the attributes of the compression system, such as near-isothermal operation, scalability, and high purity. We then developed a process cycle that could produce the compression ratio and temperature rise desired.

The next step was to determine which hydraulic fluid to use through actual testing in hydrogen at the design pressure and temperature. Advanced dynamic modeling was also done to optimize the system and determine the impact of modifying various system parameters. Then, we mechanically designed the compressor components, selected the pump, and optimized the process cycle to reduce the fabrication cost.

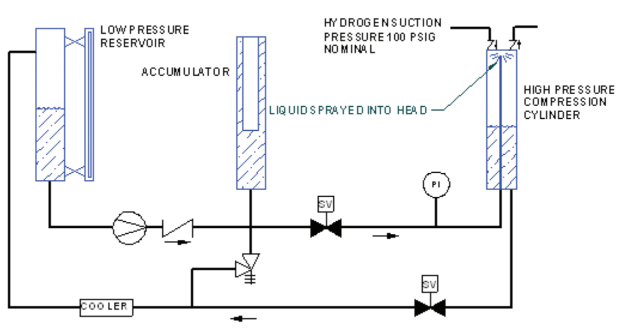

FIGURE 1. Novel Compressor Process Flow Diagram

Upon completion of the mechanical design and selection of parts, we fabricated a prototype of the isothermal compressor. Hydrostatic pressure testing and a thorough safety review, including a hazard and operability analysis (HAZOP) and a layer of protection analysis (LOPA), were performed to deal with the inherent risk of working with high pressure hydrogen.

The compressor will continue to be performance tested in a laboratory setting first with helium and then with hydrogen. The process gas will be tested for signs of oil carryover, and an oil removal system will be installed if warranted. After a period of laboratory testing, the compressor prototype will be disassembled and analyzed for signs of premature wear.

Results

Conceptual Design: We determined through design and modeling that our original target of 10°F temperature rise was not possible, due to the size of the compression chamber. We now expect a temperature rise of 50°F. This will have a slight impact on the system efficiency, but will not limit the system operation in any way.

Process Design: Several changes to the original process design included reducing the original cycle time from 30 to 10 seconds, and removing one eductor from the system. These changes were made possible by increasing the hydraulic fluid pump flowrate and horsepower, which will change the compressor's flowrate from 1 to 5 nm^3/hr. The capital cost for the compressor decreased as a result of this change. Simulated pressure and temperature curves for the new design are shown in Figures 2 and 3, respectively.

Thermodynamic Data Collection: We initially selected Krytox fluorocarbon oil based on its low hydrogen solubility and thermodynamic data. However, concern that Krytox could potentially react exothermically with hydrogen led to a change in hydraulic fluid to Inland 45, a vacuum pump oil. The hydrogen solubility of this oil is higher than that of the Krytox, but it is still below the acceptable level of 2% at the compressor's operating pressure and temperature. The measured solubility was 1.0% for a 10-second cycle. The data from the solubility test is shown in Figure 4. In addition to being completely inert towards hydrogen, Inland 45 has the benefits of lower cost and better lubrication.

Dynamic Modeling: The system surge vessels, heat exchanger, hydraulic manifold, eductor, compression chamber, and hydraulic pump process designs were finalized using ASPEN™ Dynamics modeling software,

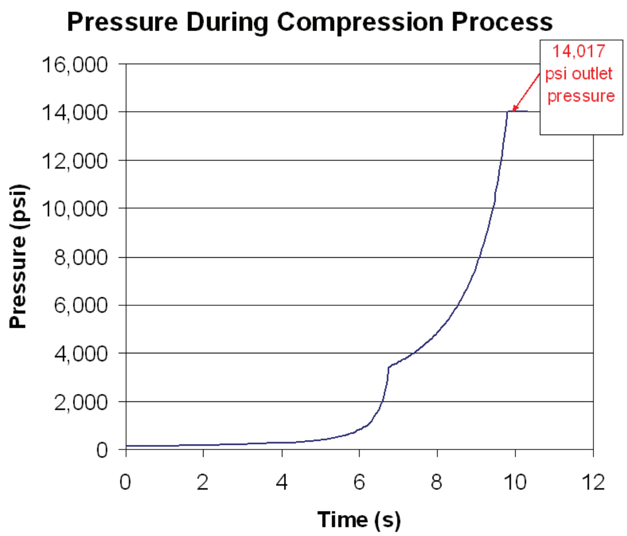

FIGURE 2. Novel Compressor Pressure vs. Time

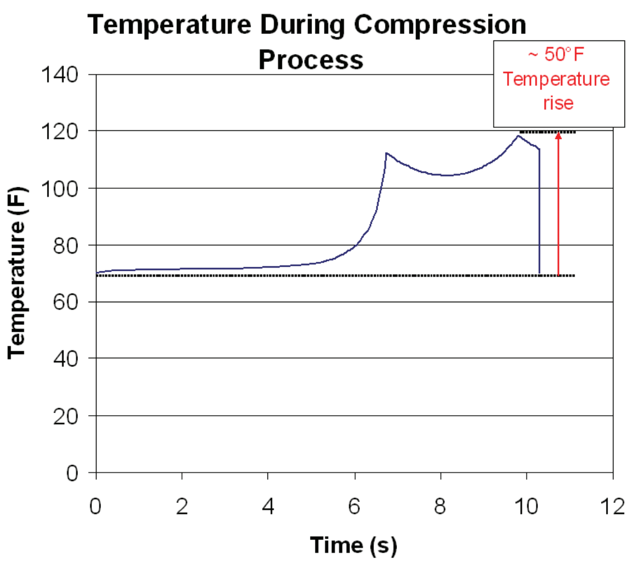

FIGURE 3. Novel Compressor Temperature vs. Time

and the hydraulic pump pressure and flowrate were optimized using this model.

Component Design, Fabrication, and Testing: The compressor components were machined in-house due to the inability of machine shops to produce a cost-effective single piece. If the compressor were built in quantities of at least 10 units per order, the machining costs would be significantly lower than for the single prototype unit that was built. Even so, the prototype compressor is 50% of the cost of a traditional hydrogen compressor with the same flowrate and compression ratio. For a flowrate of 70 scfh, the cost of compression using a traditional compressor is approximately $1.00 per kg of hydrogen. We estimate the cost of compression using

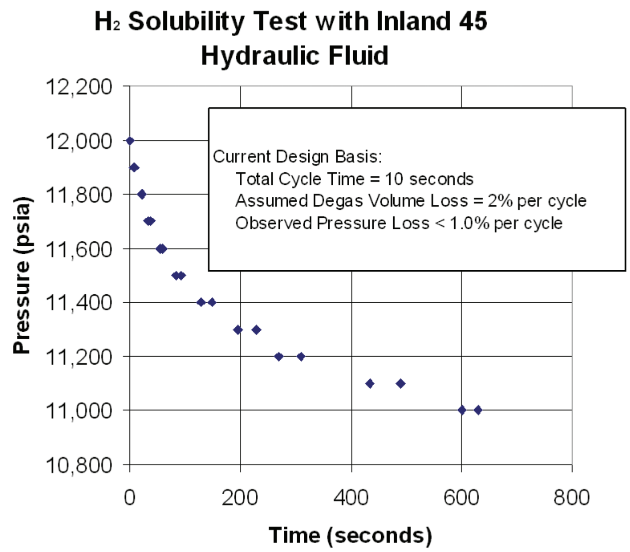

FIGURE 4. Hydrogen Solubility in Inland 45 Oil

the novel compressor prototype to be $0.40-0.50 per kg of hydrogen, and $0.25-0.30 per kg of hydrogen for the novel compressor product (based on 10 units per year). Many of the hydraulic components were designed to serve dual purposes. One example is the solenoid valve, which also acts like a check valve when de-energized, reducing the number of components required. The system control issues were also solved using customized solutions. One example is the compressor discharge check valve, which combines the check valve with the cycle completion sensor.

Prototype: Machining, assembly, and hydrostatic pressure testing of the isothermal compressor prototype are complete. A schematic and a picture of the completed prototype are shown in Figure 5. The compressor is capable of compressing from below 100 psig up to 14,000 psig, allowing it to handle all types of hydrogen sources (e.g., onsite reformation or electrolysis, regasified liquid hydrogen, delivery from tube-trailer). The compressor has been mounted to a small test skid to allow us to run the compressor and performance test it. Testing is underway with helium and will be followed by hydrogen testing. Analytical sampling will be used to verify that the level of hydraulic oil carryover is acceptable. An efficient oil removal system has been conceived in the event that it is necessary.

Safety: The most significant hydrogen hazard associated with this project is the risk of drawing air into the compressor, resulting in a potentially flammable mix of gases in the high-pressure storage vessels. To prevent this event, the compressor inlet has a low-pressure switch that is hardwired to programmable logic controller (PLC) power, and its functionality is tested every quarter. Also, a complete HAZOP and LOPA were performed, taking into consideration all physical

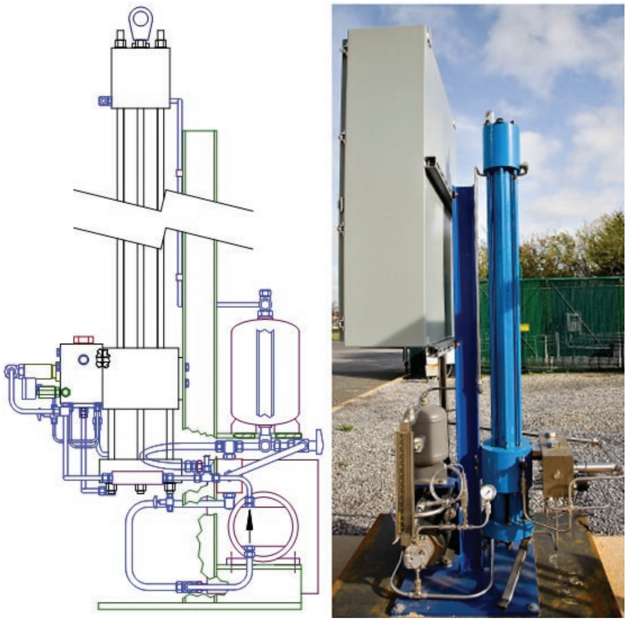

FIGURE 5. Novel Compressor Schematic (left); Novel Compressor (right)

and operating conditions before any performance testing began. Both of these analyses were completed satisfactorily. The integrity of the compression chamber was also verified and certified through hydrostatic testing. Another significant hydrogen hazard was encountered during safety reviews: the original fluorocarbon oil could, in theory, replace the fluorines with hydrogen, releasing tremendous amounts of heat and fluorine, resulting in a change to a lower cost heavy mineral oil, Inland 45.

Conclusions and Future Directions

- The isothermal compressor has significant cost, maintenance, and efficiency advantages over traditional compressors.
- A hydraulic compressor with no gas separation eliminates the issues of gas sealing and temperature rise typical of traditional compressors.
- The isothermal compression technology is technically feasible.
- The hydrogen gas will need to be analyzed for signs of oil carryover. An efficient oil removal process has been devised in anticipation of this event.
- The compressor will need to undergo long-term testing at a field site to verify initial results.
- Acceptable industrial solutions are available for all fueling components, except the cascade storage vessels.
- Automotive manufacturers are moving towards 700 barg vehicles to meet range requirements. This requires storage and a compressor system at 14,000 psig to enable fast cascade fueling.
- The major barrier to cost-effective 700 barg hydrogen fueling is the cascade storage vessels. Steel cylinders are too costly to be used (currently \$110,000 per ft^3). When approved by ASME, composite cylinders are the likely solution.

FY 2006 Publications/Presentations

1. May 2006 Annual Peer Review
2. June 2006 Technical Team Review

Special Recognitions & Awards/Patents Issued

1. Patent Pending