III.8 Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

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Mitsubishi Heavy Industries, Ltd, Compressor Corporation, Hiroshima, Japan

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Fiscal Year (FY) 2012 Objectives

Design a reliable and cost-effective centrifugal compressor for hydrogen pipeline transport and delivery:

- Eliminate sources of oil/lubricant contamination
- Increase efficiency by using high rotational speeds
- Reduce system cost and increase reliability

Technical Barriers

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

(B) Reliability and Costs of Hydrogen Compression
(I) Hydrogen Leakage and Sensors

Technical Targets

This project is directed towards the design, fabrication and demonstration of the oil-free centrifugal compression technology for hydrogen delivery. This project will identify the key technological challenges for development and implementation of a full-scale hydrogen/natural gas centrifugal compressor. The project addresses the following DOE technical targets from the Hydrogen Delivery section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan (see Table 1).

TABLE 1. Technical Targets for Hydrogen Compression

Category	2005 Status	FY 2012	FY 2017
Reliability	Low	Improved	High
Energy Efficiency	98%	98%	>98%
Capital Investment ($M) (based on 200,000 kg of H2/day)	$15	$12	$9
Maintenance (% of Total Capital Investment)	10%	7%	3%
Contamination	Varies by Design		None

FY 2012 Accomplishments

- Completed fabrication, assembly and validation testing of two 100-kW, oil-free motors.
- Completed fabrication and assembly of the single-stage compressor.
- Performed initial check-out testing of the motors and single-stage compressor system.
- Made preliminary selection of materials for the centrifugal hydrogen compressor.

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Introduction

One of the key elements in realizing a hydrogen economy is the deployment of a safe, efficient hydrogen production and delivery infrastructure on a scale that can compete economically with current fuels. The challenge, however, is that hydrogen, the lightest and smallest of gases with a lower viscosity than natural gas, readily migrates through small spaces. While efficient and cost-effective compression technology is crucial to effective pipeline delivery of hydrogen, today's positive displacement hydrogen compression technology is very costly, and has poor reliability and durability, especially for components subjected to wear (e.g., valves, rider bands and piston rings). Even so called "oil-free" machines use oil lubricants that migrate into and contaminate the gas path. Due to the poor reliability of compressors, current hydrogen producers often install duplicate units in order to maintain on-line times of 98-99%.

Such machine redundancy adds substantially to system capital costs. Additionally, current hydrogen compression often requires energy well in excess of the DOE goal. As such, low capital cost, reliable, efficient and oil-free advanced compressor technologies are needed.

Approach

The MiTi team will meet project objectives by conducting compressor, bearing and seal design studies; selecting components for validation testing; fabricating the selected centrifugal compressor stage and the corresponding oil-free bearings and seals; and conducting testing of the high-speed, full-scale centrifugal compressor stage and oil-free compliant foil bearings and seals under realistic pressures and flows in air and helium (used as a simulant gas for hydrogen). Specific tasks include: (1) Compressor design analysis – oil-free, multi-stage, high-speed centrifugal compressor system; (2) Mechanical component detailed design – oil-free bearings, seals and shaft system; (3) Detailed design and fabrication of a full-scale single-stage centrifugal compressor – for aerodynamic design verification and component reliability testing; (4) Compressor performance testing – with air and helium; (5) System design refinement; and (6) Project management and reporting.

Results

The MiTi hydrogen compressor design consists of three frames operating at the same speed with a rotor tip velocity of 1,600 fps. The system capacity is 500,000 kg/day with a pressure ratio (PR) of approximately 2.4. The mock-up of a single frame of the compressor system is shown in Figure 1. As discussed in prior reports, a single-stage compressor system has been developed to verify aerodynamics of the proposed oil-free centrifugal compressor system. The design of the single-stage compressor was described in the previous annual report.

Fabrication of the components and final assembly of the single-stage compressor and test rig has been completed (Figure 2) and initial performance verification testing has been initiated. The single-stage, 200-kW drive compressor system, consists of two 100-kW motors coupled together. The first objective of testing was to demonstrate the performance of the individual motors before testing the coupled system. Each motor was tested to full speed (60,000 rpm). Test data for one of the motors are provided in Figure 3. Testing was conducted at speeds ranging from 10,000 rpm to 60,000 rpm and stable motor speed control was demonstrated. Foil bearing temperatures were carefully monitored during testing and stable bearing performance was observed during operation. Bearing temperatures were less than 150^{o}F at full speed. During testing, cooling air was supplied externally at a rate of 15 scfm. In the final single-stage compressor, bearing cooling gas will be taken from the compressor bleed rather than externally provided. Rotor vibrations were recorded during full-speed testing using fiber-optic proximity probes. The maximum rotor motions measured at full speed were 0.0002”. This represents extremely low vibrations as it is approximately equivalent to the mechanical run-out of the rotor.

Following successful testing of the individual motors, a bladeless compressor wheel was attached to one of the

FIGURE 1. Mock-up of a single frame of MiTi hydrogen compressor exhibited at the 2012 ARPA-E Energy Innovation Summit at the Gaylord National Convention Center, National Harbor, MD.

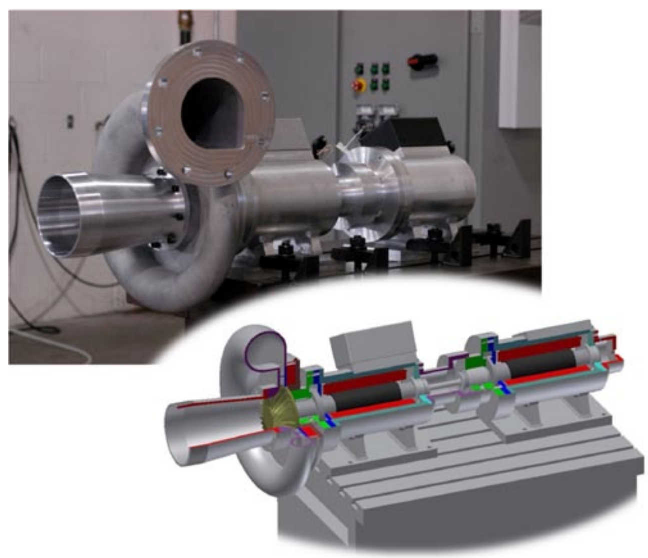

FIGURE 2. MiTi single-stage compressor driven by two 100 kW oil-free motors. Design details are shown in the inset.

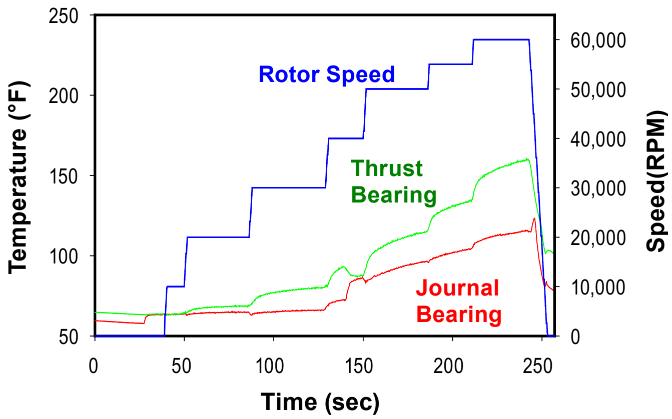

FIGURE 3. Each oil-free motor was performance tested independently up to 60,000 rpm. Both motors were thermally and dynamically stable. Maximum bearing temperature was less than 160°F and no extraneous vibration modes were observed.

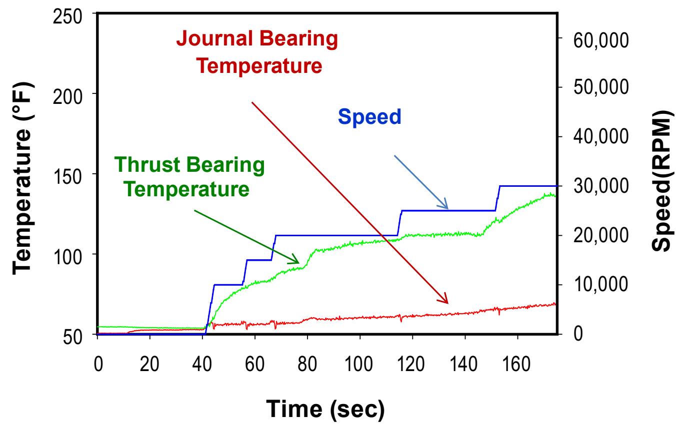

FIGURE 4. Compressor testing was successfully demonstrated up to 30,000 rpm for several 3-min test cycles. Testing to full speed of 60,000 rpm requires a dedicated reinforced test cell.

motors. The bladeless wheel was designed to have the same mass, center of gravity and inertial properties as the bladed compressor wheel. Bladeless wheel testing is a cost-effective method to demonstrate rotor dynamics and system stability before testing with more delicate and costly components such as bladed compressor wheels. The bladeless wheel testing was successful and the compressor performed as predicted. Stable operation and low foil bearing temperature were observed. Testing with the bladeless wheel was limited to 40,000 rpm for safety reasons. Testing beyond 40,000 rpm with a compressor wheel, bladed or bladeless, will be conducted after construction of the dedicated test cell with proper safety provisions.

After testing with the bladeless wheel, the bladed compressor wheel and volute were installed and tested (see Figure 2). Bearing temperatures were found to be lower in the bladed wheel (Figure 4) due to additional cooling flows, which were provided by the compressor bleed air that was not available with the bladeless wheel. Rotor vibrations with the bladed wheel were less than levels measured with the bladeless wheel and no vibration issues were observed. Testing with the bladed wheel was limited to 30,000 rpm for safety reasons. Further testing will resume when the dedicated test cell is completed. (Operation of the single stage compressor can be viewed at the following website: http://www.youtube.com/watch?v=dPn0uLIdtS8).

The dedicated test cell that will house the 200-kW single-stage compressor testing is in the process of being constructed. When completed, the test rig will be relocated in the test cell and compressor testing will resume with air and helium per the ASTM International PTC-10 standard.

MiTi has conducted a thorough literature review in order to select the most appropriate materials for use in the high-speed, centrifugal, hydrogen compressor. The material of choice requires high strength, low density, high resistance to fatigue, and an acceptable level of toughness and ductility. The data on possible materials have been discussed with experts at Sandia National Laboratories and the University of Illinois and were previously presented to the DOE. Further search of the literature was conducted recently for a separate funded project. The additional data has provided sufficient information to allow for the selection of a suitable material for the rotating group. MiTi has selected beta titanium alloys as the most appropriate material for the hydrogen compressor over other possible candidates such as high-strength steels and aluminum alloys. Beta titanium exhibits superior strength and fatigue life, particularly when exposed to hydrogen. Two beta titanium alloys were considered for the rotating group of the hydrogen compressor. Both Ti-10-2-3 and Ti Beta C are available in bar stock form and possess the necessary strength and fatigue properties (measured in air and not hydrogen). The effect of hydrogen on mechanical properties of these alloys is not well studied but limited data exist. MiTi has been able to locate one study [1] which compared Ti-10-2-3 and Ti Beta C both before and after exposure to low concentrations of hydrogen. Despite the fact that both materials are beta titanium alloys, the effect of hydrogen exposure was very different. The particular Ti-10-2-3 evaluated in that study experienced a 45% drop in yield strength but gained ductility when exposed to hydrogen, while the effect of hydrogen exposure on Ti beta C was nearly opposite. For the hydrogen compressor application, the increase in ductility is more critical than the improvement in yield strength exhibited. Therefore, MiTi recommends the Ti-10-2-3 alloy for this application.

While Ti-10-2-3 has been selected as the most appropriate material for the rotating group, this material is not available in thin foil form for the foil bearings. Therefore, following a similar material selection study, Ti-15-3 has been identified as an excellent candidate for the foil bearings and seals. This material is available in thin stock and has demonstrated excellent properties in the hydrogen environment.

Mechanical properties of beta titanium alloys are highly dependent on the exact method of heat treatment, exposure time, temperature and hydrogen concentration in service. Further data are needed in order to make a final confident selection. In the meantime, MiTi recommends a coating such as TiN or CrN to be applied to all surfaces exposed to hydrogen to further reduce the likelihood of embrittlement and degradation of mechanical properties.

Mitsubishi Heavy Industries (MHI), Compressor Corporation, has completed the design analysis of their single-entry compressor concept. The design analysis included computational fluid dynamics (CFD) performance analysis on several different design iterations. For each design concept, different axial clearances had been investigated in order to determine the sensitivity of clearance on performance. In addition to aerodynamic performance with CFD, MHI has also conducted finite element analysis (FEA) to investigate the structural integrity of the proposed impeller concepts. The FEA results revealed unacceptable local and membrane stresses in some of the impeller designs. Several modifications were evaluated to reduce the local and membrane stresses: for example, increasing the thickness of the compressor blades at the root, thereby increasing blade stiffness without unnecessary blade mass, and reducing blade lean to improve stress levels at the blade root. A successful design of the final impeller geometry has been achieved. MHI is currently designing a single-stage compressor system based on their single entry compressor design. MiTi and MHI have engaged in frequent email discussions and monthly video teleconferences to aid the collaborative effort.

Conclusions and Future Directions

During this reporting period, fabrication and assembly of the single-stage centrifugal hydrogen compressor were completed. The single-stage compressor system includes two 100-kW oil-free motors designed and fabricated at MiTi. The two motors are coupled using MiTi's proprietary mechanical coupling technology. All components of the motors and compressor, including permanent magnets, electronic drive system, sensors, compressor wheel, shafting, oil-free foil bearings, and others were acquired or manufactured. Each component was performance tested prior to incorporation into the final system. Initial validation tests of the motors indicated that each motor was capable of operating at the design speed of 60,000 rpm. Both motors independently evaluated, were thermally and dynamically stable. The compressor system driven with the oil-free motors were tested up to 30,000 rpm. The results were encouraging and no difficulties were experienced. Testing of the compressor system to 60,000 rpm requires a dedicated test cell, which is currently under construction. Once the test cell is available and testing can be performed with proper safety precautions, the compressor system will be evaluated with air and helium used as a simulant gas for hydrogen. The following tasks are planned for the remainder of FY 2012 and FY 2013:

- Single-stage performance testing in air and helium (as a simulant gas for hydrogen).
- Comparison between single-entry and double-entry compressor designs.
- Design refinements.
- Final report.

FY 2012 Publications/Presentations

1. "Oil-Free Bearings and Seals for a Centrifugal Hydrogen Compressor," invited presentation, International Tribology Conference, Hiroshima, Japan, December 2011.

2. "Oil-Free Compression for Hydrogen Delivery and Transportation," Hydrogen Delivery Technology Team Meeting, January 5, 2012, Columbia, MD.

3. "Oil-Free Centrifugal Hydrogen Compression Technology Demonstration," DOE Hydrogen Program Annual Merit Review and Peer Evaluation Meeting, May 2012, Arlington, VA.

References

1. HJ Christ, A Senemmar, M. Decker and K Prubner, "Effect of Hydrogen on Mechanical Properties of Beta-Titanium Alloys," Sadhana, 28(2003)453-465.