III.9 Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

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Subcontractor:
Mitsubishi Compressor Company (MHI), Hiroshima, Japan

Project Start Date: September 25, 2008
Project End Date: August 31, 2012

Fiscal Year (FY) 2011 Objectives

Demonstrate key technologies needed to develop reliable and cost-effective centrifugal compressors for hydrogen 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. It will identify the key technological challenges for development 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 2011 Accomplishments

- System cost analysis
- Off-design performance estimation
- Single-stage test rig design
- Manufacturing of the single-stage test rig

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Introduction

One of the key elements in realizing the 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 2% goal. As such, low capital cost, reliable, efficient and oil-free advanced compressor technologies are needed.

Approach

The MiTi® team will meet sub-program 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 conduct testing of the high-speed, full-scale centrifugal compressor stage, and oil-free compliant foil bearings and seals under realistic pressures, and flows in a hydrogen gas environment. Specific tasks include: (1) preliminary oil-free, multi-stage, high-speed centrifugal compressor system design; (2) detailed design of a full-scale centrifugal compressor stage; (3) mechanical component detailed design of the oil-free bearings, seals and shaft system needed to test the compressor stage; (4) test hardware fabrication for the single-stage compressor; (5) dynamic test; (6) compressor performance test; (7) system design refinement; and (8) project management and reporting.

Results

The design analysis of MiTi®'s proposed multi-stage, oil-free, hydrogen compressor was continued and refined. The proposed hydrogen compressor is a direct drive, multi-stage, double-entry, centrifugal compressor. Two system design points have been analyzed:

- Design Point 1: P_{IN} = 500 psig, P_{OUT} = 1,200 psig, Flow= 500,000 kg/day
- Design Point 2: P_{IN} = 350 psig, P_{OUT} = 1,200 psig, Flow= 240,000 kg/kay

For design point 1, the proposed system consists of nine stages operating at 56,414 rpm at relatively conservative tip speeds, affording a reasonable safety margin. This approach is referred to as the "high-margin" design. To achieve design point 2, higher relative tip speeds were used to achieve the required pressure and flow in six stages operating at 65,000 rpm. This approach is referred to as the "high-performance" design. To validate the feasibility of the two approaches, further detailed design and cost analysis have been conducted. Experimental validation and proof of concept will be performed in FY 2012 with a single-stage compressor test rig that has been designed and is presently being developed. Based on the scope of this project and funding made available for this effort, the single-stage compressor is being based on design point 1.

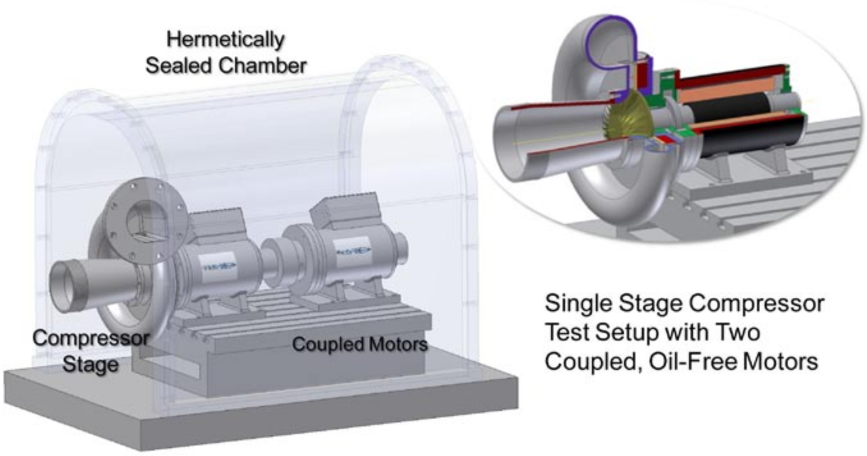

FIGURE 1. Detailed Model of the Single-Stage Compressor with Dual-Drive, Oil-Free Electric Motors

TABLE 2. Critical Nondimensional Parameters to Satisfy the Type 2 PTC-10 Test

Quantity	Symbol	Design Point Values	Type 2 Permissible Deviation
Specific Volume Ratio	vi/vd	1.072	1.018 – 1.126
Flow Coefficient	Φ	0.1253	0.120 - 0.130
Machine Mach No.	Mn	0.3266	0.141 - 0.532
Machine Reynolds No.	Rem	1.55e^{6}	1.55e^{5} – 1.55e^{7}

A detailed model of the proposed single-stage test rig is shown in Figure 1. The impeller and volute of the single-stage test rig are identical to that of a single stage within the first frame of the nine-stage system. The stage will be driven with two MiTi® oil-free electric motors, coupled together to produce up to 200 kW of shaft power. The test rig will be totally oil-free using MiTi® foil bearings and foil seals. The purpose of the single-stage testing is to validate the thermodynamic performance of the proposed centrifugal compressor design, as well as the rotor/bearing system performance under realistic speed and stress conditions expected in the nine-stage system. In order to validate the performance predictions, single stage testing will be conducted per American Society of Mechanical Engineers (ASME) performance test code 10 (PTC-10). This test code provides explicit test procedures to determine compressor thermodynamic performance with a high level of accuracy. There are two types of tests described within PTC-10; type 1 and type 2 tests. A type 1 test is one conducted with the design gas, at the design point. Under the scope of this project, testing with hydrogen is not feasible; therefore, a type 1 test will not be conducted. Since testing with all possible gases at all test conditions is often not feasible, ASME established the type 2 test based the standard design practice of compressor similitude. With this approach, key nondimensional parameters are maintained constant in testing so that thermodynamic performance of a compressor stage in one gas would apply to other gases and at other test conditions. The critical nondimensional parameters of the test stage to be held constant (within a permissible deviation) are listed in Table 2 along with the calculated values at the design point.

In the type 2 test, a similitude gas may be substituted for the design gas as long as nondimensional parameters are kept within specified limits. For this investigation, the best similitude gas is helium. Helium is an affordable and safe alternative to hydrogen with a similarly low molecular weight. It is critical that the first compressor stage performance testing not be complicated with the issues of hydrogen embrittlement. The issues of material compatibility and embrittlement are being addressed in a parallel effort in this project, but these two issues are not integrated at this time. The use of helium in these first compressor performance tests allows us to focus on aerodynamic and thermodynamic characterization and to establish a performance baseline so that any performance effects, due to embrittlement, will be apparent at a later time.

Presently, no single, direct-drive 200 kW drive motor capable of operating at 56,000 rpm exists. MiTi® has developed (with internal funds) the 60,000 rpm 100 kW motor. Since the objective of this project is to demonstrate the thermodynamic performance of the compressor, MiTi® has opted to couple two high speed 100 kW motors together to provide the needed drive power rather than develop a single 200 kW, direct drive motor. To assure stable operation of the proposed dual motor drive system for the single stage compressor, detailed rotordynamic analysis was performed. The finite element model of the coupled shaft system is shown in Figure 2. The compressor is rigidly attached to the shaft on the left. The two rigid shafts are connected by a flexible coupling (a proprietary technology developed by MiTi®). Each individual shaft is supported on MiTi® compliant foil journal and thrust bearings.

Appropriate stiffness and damping values for bearings were selected and rotordynamic analysis was conducted with DyRoBes© software (Eigen Technology Inc.). The analysis indicates that each individual shaft will be operating safely below its bending critical speed (Figure 3). All bending within the system will occur within the flexible coupling, as designed, and as has been demonstrated by MiTi® in numerous other applications. With design and analysis of the single stage test rig complete, manufacturing of the parts was initiated and is currently in progress.

In a parallel effort MHI is designing a single entry centrifugal compressor and a single-stage compressor for performance validation with assistance of MiTi®. The primary difference between the two approaches is related to the inlet flow. The MiTi design uses a double-entry technique, which splits mass flow evenly between two inlets at either end of the shaft. The benefit of this approach is inherently balanced thrust forces. The MHI design uses a single-entry approach that requires a balance piston to resolve excessive thrust loads. The advantage of this approach is that it allows for easy manipulation of axial clearance at all compressor impellers.

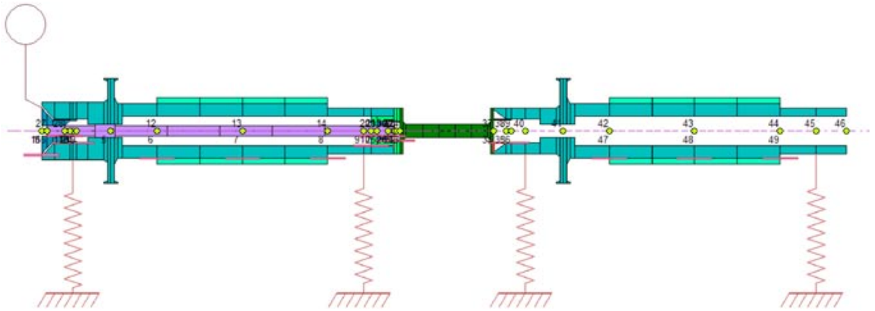

FIGURE 2. Finite Element Model of the Single-Stage Compressor And Dual-Drive System

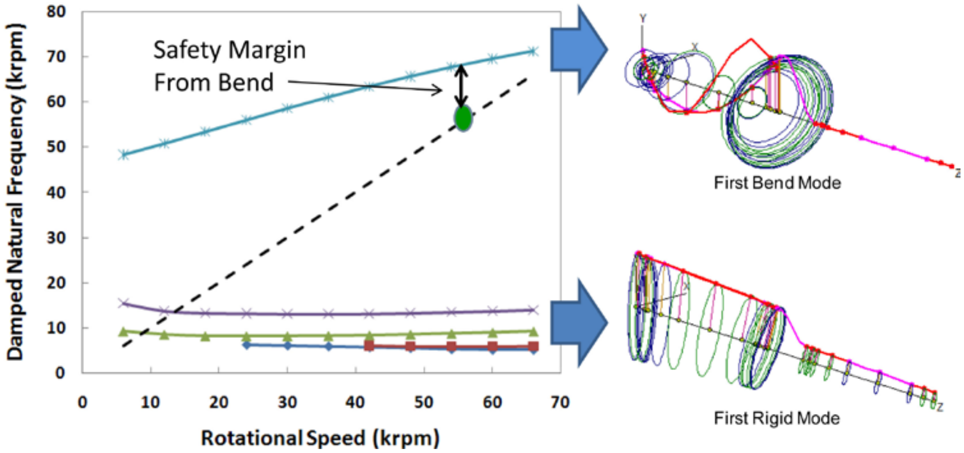

FIGURE 3. Rotordynamic Analysis of the Dual Drive Single-Stage Compressor

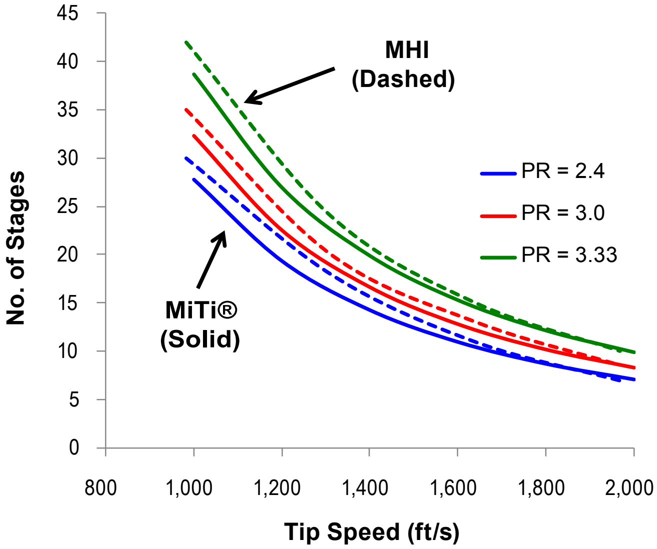

FIGURE 4. Estimation of Number of Stages Required as a Function of Tip Speed And Pressure Ratio (PR)

Despite the differences in design approaches, the overall performance of the two systems will be very similar. In Figure 4, independent results from MiTi® and MHI are presented. The number of stages required to reach a particular pressure ratio are presented as a function of tip speed. Despite the use of double- and single-entry compressor designs, the results from MiTi® and MHI correlate well, especially at higher tip speeds within the expected operating range. This is because the inlet conditions, fluid properties and design point used for each concept were identical. MiTi® and MHI both assumed similar conditions and both employ highly sophisticated, but different, software design tools.

Conclusions and Future Directions

During this reporting period, further design refinement was conducted. To demonstrate the feasibility of MiTi®'s design concept, a single-stage test rig was designed and fabrication of components was initiated. In parallel, a single-entry compressor concept is being developed with guidance from MiTi® by MHI. The following tasks are planned for the remainder of FY 2011 and FY 2012:

- Complete fabrication of single-stage compressor components for testing.
- Validate the proposed single-entry and double-entry compressor designs using performance data from the single-stage compressors.

FY 2011 Publications/Presentations

1. Heshmat H., Walton J.F., "Oil-Free Modular System Designs for Industrial Compressors and Renewable Energy Turbine Generator Systems," Clean Technology Conference and Expo, June 21, 2010, Anaheim, CA.

2. Heshmat H., Hunsberger A.Z., Ren Z., Jahanmir S., Walton J.F., "On the Design of a Multi-Megawatt Oil-Free Centrifugal Compressor for Hydrogen Gas Transportation and Delivery – Operation Beyond Supercritical Speeds", Proceedings of the ASME International Mechanical Engineering Congress and Expo, November 12-18, 2010, Vancouver, BC, Canada.

3. Heshmat H., *Invited Keynote*, "Tribological Requirements of High-Speed Oil-Free Rotating Machinery for Hydrogen Applications," 2011 Hydrogenous Tribology Symposium, February 3, 2011, Fukuoka, Japan.

4. Heshmat H., "Design of a Multi-Megawatt Oil-Free Centrifugal Compressor for Hydrogen Gas Transportation and Delivery," Fuel Cell and Hydrogen Energy Expo, February 15, 2011, National Harbor, Md.