III.6 Advanced Sealing Technology for Hydrogen Compression

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Objectives

Develop and demonstrate feasibility of using a close clearance, non-contacting, and dynamic compliant foil seal in hydrogen and/or natural gas pipeline compressors.

- Reduce leakage rate of hydrogen.
- Reduce system cost and increase reliability.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure 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 development of oil-free gas seal technology for hydrogen transportation and delivery compressors. The developed foil seals will be tested to assess the leakage flow as a function of differential pressure. The project addresses the DOE technical targets from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan shown in 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 of H_2/day)	$15	$12	$9
Maintenance (% of Total Capital Investment)	10%	7%	3%
Contamination	Varies by Design		None

Accomplishments

- Performed preliminary static tests using the seal design established in Phase I. Flow factor data (for seal leakage analysis) both in air and helium obtained for the preliminary designs of MiTi® Seals indicated that very low leakage rates can be obtained.
- Developed a new analytical method that combines finite difference fluid mechanics analysis and finite element structural analysis as an efficient and robust method for analysis of high-speed seal designs.
- Designed and evaluated two test rigs for low-speed and high-speed dynamic testing of foil seals. Comprehensive rotor dynamic analysis of these test rigs demonstrated that the test rigs should provide smooth rotation for testing of foil seals at a wide range of speeds.

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Introduction

The objective of this Small Business Innovation Research project is to develop and demonstrate the feasibility of using a close-clearance, non-contacting, and dynamic compliant foil seal in hydrogen and/or natural gas pipeline compressors. The goal of this seal is to enhance the economic viability of hydrogen as an energy carrier and to substantially improve the efficiency of centrifugal compressors so that they become feasible for use in transportation and delivery of hydrogen. Under Phase I, MiTi completed the design of a compliant foil seal suitable for the previously sized hydrogen transportation and delivery compressors and fabricated the designed seal and tested it statically to assess the leakage flow as a function of differential pressure. Results showed considerably reduced leakage with the foil seal over other technologies and previous versions of the compliant foil seal. Under Phase II, the foil seal design is to be refined based upon lessons learned from Phase I; additional static testing is to be conducted to validate the design; and finally, dynamic testing of the final full-scale design will be completed to demonstrate that performance capabilities meet the specified needs of a hydrogen transportation and delivery compressor.

Approach

Additional testing will be performed using the seal design and hardware developed under Phase I to further characterize the secondary/tertiary losses and to assess approaches to reduce the secondary losses. The design will be revised to mitigate secondary leakage losses. Full-scale compliant foil seals will be tested under dynamic rotating shaft conditions. The critical foil seal dimensions and operating clearances will be selected to minimize leakage between stages of a hydrogen transportation centrifugal compressor capable of delivering up to 1,000,000 kg/day. Ambient hydrogen gas pressures, pressure rise per stage, shaft surface speed and expected rotor motions will be included in the analysis and seal design. A new test rig (or modifications to an existing test rig) will be developed to evaluate and characterize the seals under realistic operating conditions of speed, rotor radial displacements and differential pressures. The full-scale seals will be evaluated with the dynamic test rig to determine leakage and differential pressures representative of that expected in an operating hydrogen centrifugal compressor. During testing key parameters, such as upstream and downstream pressure, leakage flow, shaft speed, rotor radial motions and seal foil, temperatures will be measured. Based upon test data, the compliant foil seal design will be revised to address identified areas for improvement. A final report documenting the key seal design parameters and component sizing, the test results and an assessment of the benefits of the seal to the performance of hydrogen compressor will be prepared.

Results

Several variations of the baseline seal configuration were evaluated under static flow conditions (i.e., no shaft rotation). Parameters investigated included number of top foils, primary bump size, radial clearance and direction of flow through the seal. During each test, the gas inlet pressure and mass flow into the seal were measured in order to determine seal leakage rate, both in total mass flow and flow factor.

Since previous testing revealed that leakage through the seal secondary passages could be reduced by modifying the seal design: preliminary testing with different seal configurations was conducted. The results of tests performed with different seal configurations are shown in Figure 1. Modification of the seal design significantly reduced leakage by sealing the secondary flow path. While this improvement is seen in the static seal test, the effect of rotation on seal performance will be determined when the dynamic test rig becomes available for use.

A series of experiments was performed to test the effects of leakage as a function of bump height and different radial clearances. Larger bumps allow the seal to accommodate greater radial excursion by the rotor; and as expected, larger radial clearance causes larger leakages.

The back face of the static seal test chamber was modified to have a controlled orifice so that different downstream pressures could be evaluated while still achieving the same differential pressures. The modified rig for static seal testing is shown in Figure 2. High pressure bottled air and helium were used at differential pressures up to 100 and 250 psig, respectively, in these tests. To address the influence of compressibility on the gas, the tests were conducted at both ambient and elevated downstream pressures. In addition, the seal durability was assessed under continuous high differential pressures.

The three potential leakage paths were identified, where the primary flow runs in parallel with the shaft, the secondary flow travels up the front face of the flange fingers and down their back face, and the tertiary flow travels through the finger slots. The seals with two, three and four smooth foil layers were tested to increase the flow resistance in the region of the flange fingers. To characterize the losses through each leak path, the total leakage was measured first. The smooth foil surface that runs in parallel with the shaft was then "glued" to the shaft to eliminate leakage through the primary path

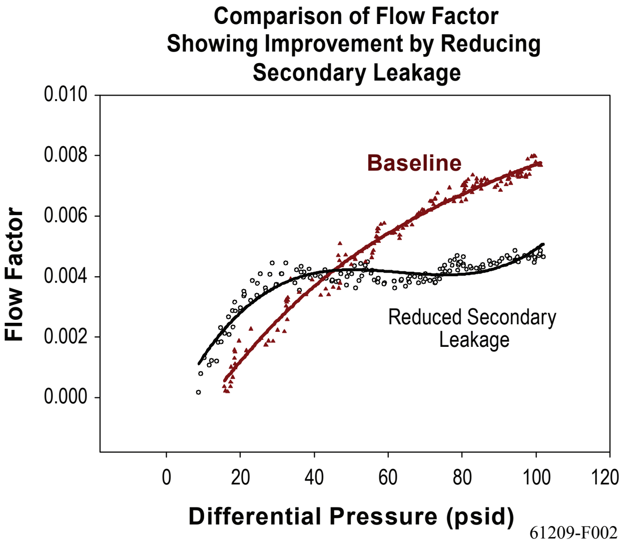

FIGURE 1. Static Sealing Improvement of a Radial Foil Seal

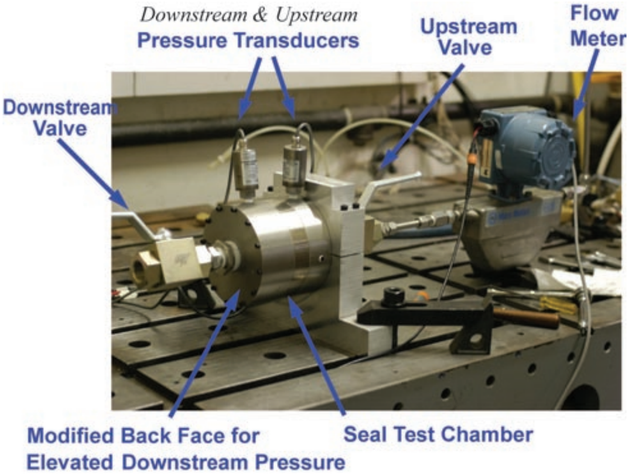

FIGURE 2. Modified Static Seal Test Rig

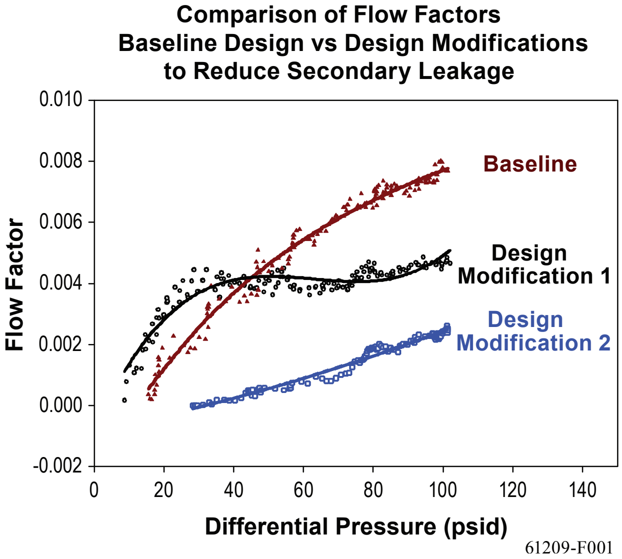

FIGURE 3. Comparison of Flow Factor up to 100 psig for the Several Foil Seal Configurations

and, thus, allow measurement of leakage through both the secondary and tertiary paths. Next, a polymer ring replaced the face bumps to further eliminate the leakage through the secondary path; therefore, the leakage only through the tertiary path could be determined.

The flow factors for several foil seal configurations in helium are compared in Figure 3. The flow factor can be substantially decreased by modifying the foil seal design.

Two durability tests were conducted with a two-foil seal under continuous high differential pressures. The test in helium was carried out first and the seal subjected to a differential pressure of 100 psig for about seven minutes. The same seal continued to be tested in air. The seal was subjected to high differential pressure up to 100 psig for more than ten minutes. The seal was examined after these two tests and no sign of any damage was observed.

In order to properly design a high-efficiency foil seal, a universal model is needed for the analysis. This model should be readily modified to take into account various seal/hydrodynamic compliant surfaces under hydrostatic loading (differential pressure across the seal plus hydrodynamic pressure due to runner velocity and eccentricities). While present MiTi® analytical computer programs can be used for this task, they do not include a provision for the reaction of the top elastic and smooth foil to the applied pressure and the deformation of the underneath compliant elements. By including smooth foils and possibly surface coatings, we will have a better understanding of fluid film thickness variations in between the bearing/seal interfaces. A numerical technique has been developed to merge finite element analysis (FEA) with finite difference analysis (FDA) and has been proven to provide successful results. This technique combines the governing equations of elasticity with hydrodynamics and solves multi-level, non-linear algorithms using the above numerical methods. We have basically taken advantage of each numerical method's strength and have combined them in such a way, enabling us to achieve numerical convergence, reduce the number of iterations needed for the computations and enhance our understanding of compliant foil seal behavior under various fluid film pressures.

One smooth top foil pad of the compliant surface foil seal was modeled as a 2-dimensional shell. The model included 51 nodes in the tangential direction and 11 nodes in the radial direction. A finer mesh was used in the trailing portion due to the higher pressures expected in that region from the hydrodynamic film calculations. The bump foils were modeled as grounded spring elements at the nodes of the shell elements. A total of 500 quadrilateral 2-dimensional shell elements and 561 point elements were used in the finite element model.

Based on the initial foil seal geometry and boundary conditions, the stiffness of the bump foils was calculated using a custom finite difference program. Applying the local pressure-deflection relationship, the pressure profile was predicted through the hydrodynamic finite difference analysis. In the finite element model, the leading edge was kept fixed in all degrees of freedom. The pressure profile predicted by the hydrodynamic analysis was applied at the nodes of the shell elements as element variable pressure. The stiffness values accounting for the bump foils from the finite difference program were converted to the spring constants at the nodes of the shell elements in order to take the variation in element sizes into account. The linear static structural analysis by finite element method was conducted using MD Nastran from MSC Software Corporation.

Using the pressure profile provided by the hydrodynamic analysis and the deformation results computed by the structural FEA, the stiffness values that include the effects of both the smooth top foil and bump foils can be calculated. These new stiffness values are then used in the next iteration of the hydrodynamic analysis. This procedure repeats until the pressure solution converges.

The seal design and analysis technique was used to perform a parametric study. In each case, three conditions were analyzed, where the first one has a uniform mesh in the angular direction with constant bump stiffness at all nodes, the second one has a finer mesh near the trailing edge in the angular direction with constant bump stiffness, and the third one has a uniform mesh in the angular direction with variable bump stiffness generated by iterations between the FDA and FEA. The un-deformed and deformed shapes of the smooth foils from the structural FEA were determined for each case. The modeling and analysis techniques developed will be used for design analysis of the desired foil seals for the hydrogen compressor.

An existing test rig was modified and refurbished for seal testing under dynamic conditions (i.e., rotating shaft). This hardware consists of a MiTi® 42 hp, 60,000 rpm, oil-free motor, a high-speed quill coupling and a rolling element supported spindle. The shaft of this spindle was modified to accept an existing precision test journal. The grease packed angular contact bearings in the spindle have a speed limitation of 15,000 rpm. This configuration will allow testing at up to 75% of the target surface velocity for the project. A separate, oil-free seal test spindle is being designed to allow testing up to the maximum desired surface speed.

The dynamic stability of the test rig was analyzed to ensure stable operation. The rotordynamic analysis indicated that all anticipated rotor motions would be within the system capabilities. The low-speed test rig shown in Figure 4 has been fabricated and evaluated. The test assembly was operated at speeds up to 14,000 rpm where synchronous rotor response reached a maximum of 0.002 inches peak. Shaft radial motion was monitored with eddy current proximity probes. The fast fourier transform spectrums of the experimental rotor displacements measured by two orthogonal sensors at the middle of the seal location for a similar set of speeds were compared with the predicted values.

Two separate foil seals were tested simultaneously. A total of 19 runs were performed in the low-speed test rig. Testing included static and dynamic testing with varying the differential pressure and rotational speed. The foil seals were initially tested with two top foils. In order to improve the sealing performance, a third top foil was added to provide a more tortuous path and reduce secondary leakage. Typical leakage and flow factor results are shown in Figure 5. At 14,000 rpm and 75 psi pressure, a low flow factor of nearly 0.012 was achieved.

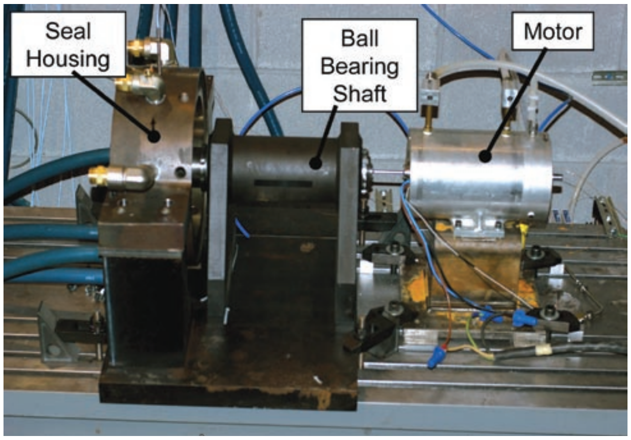

FIGURE 4. The Low-Speed Test Rig Driven with the MiTi® electric motor

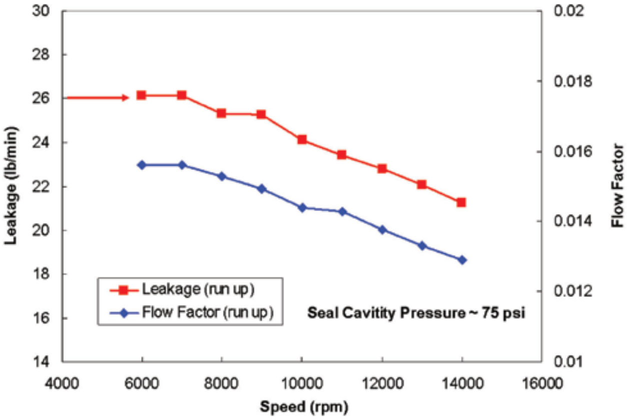

FIGURE 5. Leakage and Flow Factor Data as a Function of Speed

Results obtained with the 14,000 rpm test rig have successfully demonstrated stable dynamic performance of a foil seal at surface velocities very near the proposed 650 ft/sec. For these dynamic verification tests, leakage rates of the present seal design are larger than predicted because radial shaft clearance was kept larger than necessary. Now that dynamic baseline performance is demonstrated, tighter radial clearances will be tested and leakage rates will decrease drastically.

A high-speed test rig is needed to conduct dynamic testing of the seals at rotational speeds up to 60,000 rpm. Several design iterations were considered and evaluated, and the corresponding rotor dynamic analysis was conducted to predict the system stability. The final design consists of a permanent-magnet motor drive, a coupling and an interchangeable seal test journal attached to the spindle through a tie bolt. The motor is supported by two mechanical ball bearings and the spindle is on two foil journal bearings. Detailed drawings have been prepared and the required components are being acquired to fabricate the test rig.

Conclusions and Future Directions

The tasks selected for the first year have been successfully completed. The results of static flow tests, in which various seal parameters were varied, indicated that very low leakage values could be obtained. A new analytical method that combines finite difference fluid mechanics analysis and finite element structural analysis was developed for analysis of high-speed seal designs. Several possible seal designs were evaluated with the developed analytical method. Two test rigs were designed for low-speed and high-speed dynamic testing of foil seals. Comprehensive rotor dynamic analysis of these test rigs demonstrated that the test rigs should provide smooth rotation for testing of foil seals at a wide range of speeds. Fabrication and check out of the low-speed test rig was completed. The high-speed test rig is currently under construction. The following tasks are planned for next year:

- Finalize the design of the oil-free foil seals.
- Fabricate and fully evaluate performance of selected seals.
- Modify the seal design if necessary.
- Prepare the final report.

FY 2009 Publications/Presentations

1. "Oil-Free Rotor-Bearings and Seals for Hydrogen Compression," DOE Hydrogen Program Annual Review and Peer Evaluation Meeting, May 2009, Arlington, VA.