Development and Testing of a Toroidal Intersecting Vane Machine (TIVM) Air Management System

Sterling Bailey (Primary Contact), Steve Chomyszak
Mechanology, LLC
453 South Main Street
Attleboro, MA 02703
Phone: (408) 472-3719; Fax: (408) 358-4012; E-mail: sterling@mechanology.com

DOE Technology Development Manager: John Garbak
Phone: (202) 586-1723; Fax: (202) 586-1637; E-mail: John.Garbak@ee.doe.gov

ANL Technical Advisor: Robert Sutton
Phone: (630) 252-4321; Fax: (630) 252-4176; E-mail: Sutton@cmt.anl.gov

Objectives

- Develop a Toroidal Intersecting Vane Machine (TIVM) air management system that satisfies DOE's automotive fuel cell system requirements and is readily adaptable to alternate user requirements.
- Select and demonstrate design features to assure adequate sealing, minimum porting pressure loss, and low friction operation.
- Develop the TIVM design methodology to allow efficient application to alternate user requirements.
- Develop manufacturing processes for low-cost high-volume production.
- Measure the performance of the TIVM compressor/expander across the operating range.
- Fabricate and deliver a compressor/expander/motor prototype for independent testing.

Technical Barriers

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

- A. Compressors/Expanders

Approach

- Demonstrate the basic performance of the TIVM concept as a compressor/expander.
- Test candidate materials for friction and wear using standard laboratory tribilogical methods.
- Test candidate seal and port designs as well as low friction materials in simplified test configurations to select the best performing options for the TIVM compressor/expander.
- Optimize the vane surface solution methodology to provide a more efficient design process.
- Fabricate a TIVM compressor/expander prototype using seals, porting, and materials selected from the simplified feature tests and evaluations.
- Conduct performance tests of the prototype covering the full operating range.
- Refine the prototype features as necessary to obtain optimal performance.
- Develop cost efficient manufacturing methods for high volume production.
- Integrate a high efficiency motor with the TIVM prototype and test the combined unit across the operating range.

- Deliver a TIVM compressor/expander/motor (C/E/M) prototype to Argonne National Laboratory (ANL) for testing.

Accomplishments

- Friction and wear tests with the primary material pair for the TIVM vanes have shown that these materials will meet the operating and lifetime requirements. Testing has been performed at two independent laboratories.
- A simplified single vane test (SVT) rig has been designed, fabricated and operated to screen seal design concepts and low friction materials.
- Computational Fluid Dynamics (CFD) calculations were performed to guide seal designs.
- Several seal design concepts were developed and tested ; three of them met both leakage and friction requirements.
- Design optimization has reduced maximum speed from 4800 rpm to 3200 rpm with no increase in volume.
- Experimental expander vanes are being fabricated to potentially qualify a unique powder metallurgy process that provides net shape, finish, and hardness without secondary operations.
- A theoretical mathematical analysis of the surface solution methodology has been used to provide a significantly improved surface definition.
- Initial thermal analyses have been performed to evaluate geometric changes caused by differential thermal expansion.

Future Directions

- Complete seal measurements for combined leakage and friction characteristics and confirm satisfactory performance of at least one design.
- Perform porting feature measurements to confirm satisfactory performance.
- Complete investigation of the additional TIVM innovation with potential to reduce the required shaft power by >1kW.
- Build a fully operational prototype with selected seals and ports and measure the integral performance.
- Integrate a high efficiency motor and measure performance of the combined C/E/M unit; deliver to ANL for testing.

Introduction

The Toroidal Intersecting Vane Machine (TIVM) is an innovative mechanical concept, invented and patented by Mechanology, which can be configured as an integrated, positive displacement compressor/ expander or compressor/compressor. In FY 1999, DOE investigated the TIVM concept for potential application to automotive fuel cell systems and determined that the inherent efficiency, compactness and thermodynamic attributes of this concept might be of significant benefit. Mechanology developed a design specifically for the 50 kWe automotive system and evaluated its potential performance. Based on the encouraging results obtained, a first generation compressor/expander prototype was built and tested. Figure 1 illustrates this prototype partially assembled to show the compressor and expander. The compressor/expander prototype tests indicated that the TIVM runs smoothly with no mechanical problems; however, improvements are required to limit air leakage. Additional tests using the generic prototype with temporary seals demonstrated the capability of the TIVM to produce the necessary flow and pressure. Based on these observations, the TIVM compressor/expander development plan is focused on development and demonstration of seals, ports and low friction materials. These are necessary

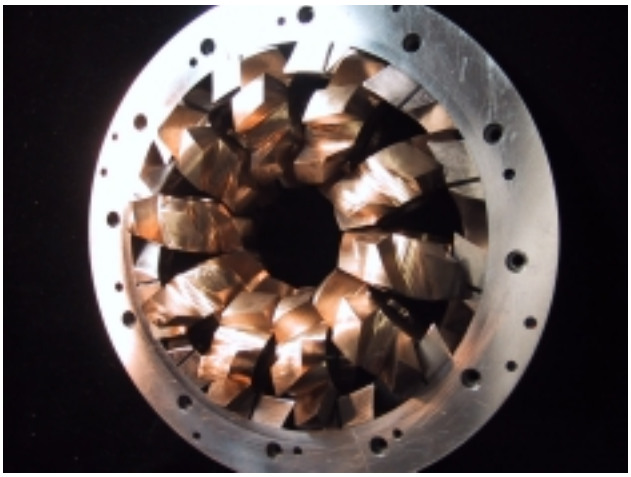

Figure 1. Partially Assembled First Generation TIVM Compressor/Expander Prototype

to satisfy the functional performance requirements with low parasitic power. Although not the main focus of the current development project, the requirements for air management system packaging, noise, and cost are considered as critical for a successful TIVM based system and are carefully considered as development progresses.

Approach

The basic functions of the TIVM compressor/ expander (kinematics, pressure, flow) have been demonstrated; however, development and qualification of specific seals, flow ports and low friction materials are required to meet the performance requirements.

During 2003, Mechanology has focused on the use of simplified feature tests to allow rapid, efficient characterization of a broad range of design options for later inclusion in a full TIVM device. The initial simplified tests use a single vane test (SVT) device to measure the leakage and friction characteristics of candidate vane seal designs. Computational Fluid Dynamics (CFD) analyses of the vane/housing/air interactions have been used to guide the design and testing of these features. Additional tests will be performed using the SVT device to finalize the seal designs to be used in the next TIVM compressor/ expander prototype.

Definition of the vane surface configurations required for a specific TIVM can be accomplished through an iterative process developed by Mechanology. With sufficient iterations, a very good meshing surface solution can be obtained, as evidenced by the generic TIVM prototype vanes. However, this process is quite time consuming. Mechanology has explored alternate mathematical approaches to develop a more efficient surface design methodology.

Low friction materials are necessary for the intersecting vanes to realize the predicted energy efficiency of the TIVM compressor/expander. Additionally, these materials must have sufficiently low wear under the TIVM operating conditions to perform acceptably during a 6,000 hour lifetime. Several candidate material pairs and potential coatings have been identified based on published data. To qualify materials for the TIVM, standard laboratory friction and wear tests are being performed. Successful materials are being tested in the single vane test rig, and subsequently, the best materials will be used in a TIVM prototype.

In parallel with the specific technology development for the TIVM, Mechanology continues to evolve the overall design to reduce the operating speed and increase the efficiency. The improved design features will be incorporated into the subsequent prototypes.

One or more full TIVM compressor/expander prototypes will be fabricated by Mechanology and tested across the full operating range. Modifications will be made as necessary to optimize performance. Subsequently, a high efficiency electric motor will be integrated with the TIVM to form a complete compressor/expander/motor component. This unit will be tested by Mechanology and then delivered to ANL for independent testing.

Results

ANL has constructed a tribology test rig that operates at the speed and interface pressure of the TIVM compressor/expander vanes at full power. During 2003, ANL resolved vibration problems with the test rig and performed friction and wear tests with stainless steel and low friction engineered polymer

samples provided by Mechanology under both dry and high humidity conditions. These measurements have indicated an acceptable friction coefficient at the TIVM operating conditions and wear rate consistent with the lifetime requirement.

A simplified single vane test rig has been designed, fabricated and made operational for screening of seal designs and testing of low friction materials with vanes traveling at speeds in the planned operating range. Figure 2 illustrates the single vane test device design with the pressure cover removed. This device permits parametric variation of clearances and seal preloads as well as rapid change-out of materials and seal designs. The computer control and data acquisition program allows testing at specified speeds and pressure differentials with automated data logging.

CFD calculations were performed by ANL using Mechanology's single vane test configuration. These analyses have been used to understand the interaction of the vane/seal/air system as a function of operating conditions and to guide seal designs. Based on these results, non-contact seals were eliminated from the design concept options, and compliant contact seals have been selected.

Figure 2. Single Vane Test Equipment

Mechanology has analyzed all of the potential leakage paths for both the compression and expansion cycles and has developed time histories of the pressure differentials across each path throughout the cycle. These data quantify the driving potential for leakage from the compression and expansion chambers.

Mechanology reviewed the development of state-of-the-art seals relevant to the TIVM requirements. We found that the brush seals developed for jet engine and turbine applications will more than meet our requirements for some locations. Based on the seal study, new configurations were developed for the remaining TIVM seal locations, and samples were prepared for testing in the SVT rig. Tests were performed for leakage and friction individually to give accurate measurement of the very small values, and combined dynamic tests were performed for the combined behavior. Several design concepts were eliminated because of excessive leakage or friction. Figure 3 illustrates an example of the pressure vs. time data from a seal dynamic test. Pressures in excess of 7 atm have been generated at relatively low speeds, indicating the effectiveness of the seals. Three design concepts met both the leakage and friction requirements.

Detailed analysis of the TIVM operation and the sources of inefficiency have shown the potential for a modified TIVM geometry that has significantly reduced friction. Patent disclosures are being prepared prior to release of the details of this additional innovation.

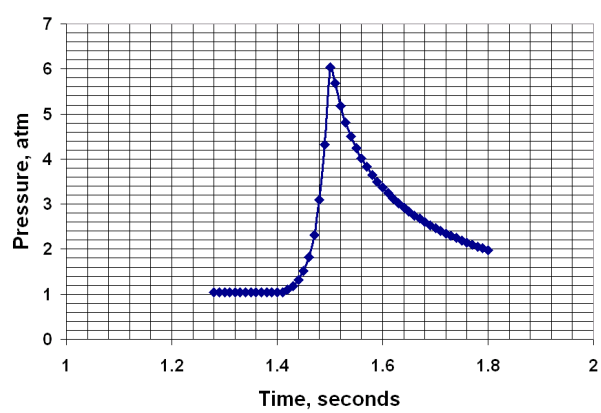

Figure 3. SVT Pressure vs. Time Example Data

Conclusions

Design and analysis of the first generation TIVM compressor/expander has shown that this concept has the potential to meet the DOE requirements for automotive fuel cell applications with significantly better performance than other options. Testing of the compressor/expander and generic TIVM prototypes has demonstrated correct kinematic functioning and the capability to produce the required pressure and flow. These tests have also highlighted the need for efficient seals and flow ports in the TIVM. Laboratory tribology measurements have shown acceptably low friction and wear for the preferred material pair candidate for the intersecting vanes. The ongoing development program is focusing on selection of seals, porting, and material options through simplified feature tests and then sequentially more prototypic TIVM tests. The single vane test results indicate that there are multiple seal design concepts that meet both leakage and friction requirements. Using the leakage and friction characteristics of one option tested, the expected power required to drive the TIVM compressor/ expander at full flow is approximately 6 kWe, as shown in Figure 4. A fully prototypic TIVM compressor/expander/motor will be fabricated and tested to measure actual performance with the selected options. Subsequent work will include development and qualification of cost efficient manufacturing methods for high volume production and development of features to assure compliance with noise requirements. Additional testing will focus on operating environment and reliability/ endurance issues.

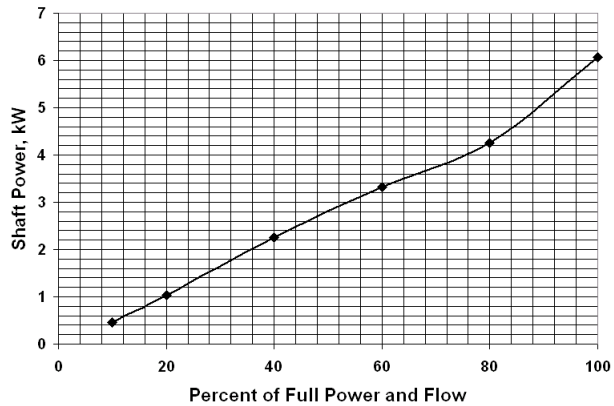

Figure 4. Expected TIVM Power for 50 kWe System

FY 2002 Publications/Presentations

1. "Toroidal Air Management System Development and Testing Status", presented to the FreedomCAR Technical Team, April 16, 2003.

2. "Development of a Toroidal Intersecting Vane Machine Air Management System for Automotive Fuel Cell Systems", presented at the DOE Hydrogen and Fuel Cells 2003 Annual Merit Review, May 22, 2003.

4. "TIVM Compressor/Expander/Motor Development and Demonstration, Cooperative Agreement DE-FC04-02AL67626, Annual Technical Progress Report - November 2001 to December 2002 and Quarterly Progress Report – October 2002 to December 2002", submitted January 30, 2003.