Development and Test of the Toroidal Intersecting Vane Machine (TIVM) Air Management System

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May 26, 2004

This presentation does not contain any proprietary or confidential information
The overall objective of this program is to develop the innovative TIVM concept into working compressor/expander/motor hardware that satisfies the FreedomCAR Guidelines – and is easily adaptable to individual car system requirements – and to measure the TIVM air management system performance.

Objectives for the past year - building on the prior demonstration of the basic functionality of the TIVM:

- Develop a compressor/expander design concept to limit friction, air leakage, and porting losses to meet FreedomCAR power and efficiency targets
- Develop a detailed design for a prototype compressor/expander
- Begin fabrication of the prototype compressor/expander with the selected features
• Total funding - $2,736,900
• DOE share - $2,000,000
• Mechanology Cost Share - $736,900
  i.e. 26.9%
• GFY03 funding - $450,000
The Objective of Mechanology’s TIVM CEM Development and Test project is to overcome the following Transportation Systems Barrier identified in the HFCIT Program Multi-Year Program Plan:

“Compressors/Expanders. Automotive-type compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available. To validate functionality in laboratory testing, current systems often use off-the-shelf compressors that are not specifically designed for fuel cell applications. These result in systems that are heavy, costly, and inefficient. Automotive-type compressors/expanders that meet the FreedomCAR technical guidelines need to be engineered and integrated with the fuel cell and fuel processor so that the overall system meets packaging, cost, and performance requirements.”
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>91g/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>2.5 atm</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>5.8 kW</td>
</tr>
<tr>
<td>Size</td>
<td>15 liters</td>
</tr>
<tr>
<td>Weight</td>
<td>15 kg</td>
</tr>
<tr>
<td>Noise</td>
<td>&lt;65 db</td>
</tr>
<tr>
<td>Cost</td>
<td>$400</td>
</tr>
<tr>
<td>Turndown Ratio</td>
<td>10</td>
</tr>
<tr>
<td>Durability</td>
<td>5000 Hours</td>
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</table>
TIVM Development Technical Approach

- TIVM Description and Unique Features
- Prior Technical Status – Demonstrated Basic Functionality
- Identify Key Technical Challenges to Meet DOE Targets
- Develop Key Components Through Feature Testing and Analysis
- Integrate Features Into C/E Prototype Conceptual Design
- Develop Detailed Design with Engineering Analysis Support
- Fabricate and Test C/E Prototype for Integral Performance
- Refine C/E Prototype as Needed to Satisfy DOE Targets
- Integrate Motor with Compressor/Expander
- Fabricate, Test, Deliver CEM to DOE for Independent Testing
The Toroidal Intersecting Vane Machine Concept
Toroidal Intersecting Vane Machine Characteristics

Positive Displacement
- Compressor/Expander
- Compressor/Compressor
- Blower

High Flow

High or Low Pressure

Small Volume

Low Production Cost

Many Spin-off Products

TIVM Attributes Provide Efficient Operation as an Integral Compressor/Expander for Automotive Fuel Cell Applications With Very Good Performance at High Turndown Ratios
The Basic Viability of the TIVM Has Been Proven Through Hardware and Tests
Three Key Performance Issues Needed to Satisfy the Power Requirement

• Seals to limit air leakage without adding excessive friction

• Porting to assure low pressure drop, and power loss, across the compressor and expander inlet and discharge paths

• Confirmation of coefficient of friction for meshing vane interface – including high humidity environment

These are not unusual engineering tasks that require inventions or new materials. Solid, disciplined engineering development will provide the required solutions.
Safety

• Failure modes and effects analyses will be used to identify and evaluate potential TIVM air management safety risks
• Fault trees will be constructed and evaluated
• Potential hazards include operation of rotating equipment at \( \sim 2000 \) RPM with potential mechanical failure
  – Robust design and large margins mitigate this risk
• Materials of construction could pose risk
  – No hazardous materials identified to date
TIVM Development Timeline

- TIVM Concept Invented at Stanford
- Mathematics Developed
- US and Foreign Patents Granted
- Software Developed
- Generic Prototype Built
- DOE Contract Award
- TIVM CEM Prototype Due
- Fabricate TIVM CEM Prototype, Measure Performance, Deliver
- Pressure and Flow Demonstrated
- Friction, Sealing, and Porting Tech Solution
- Single Vane Test Rig Operational
- DOE Contract Start
- Calendar Year 2001
- Calendar Year 2002
- Calendar Year 2003
- Calendar Year 2004
- Calendar Year 2005
- Calendar Year 2006
Technical Accomplishments/Progress

- Major innovation in TIVM conceptual design developed, patents submitted
- Significantly improved vane surface solution – performance impact tested
- Rotary Seal Test Machine built for qualifying face seals
- Detailed Compressor/Expander design and analysis completed
- Fabrication of prototype begun
New TIVM Design Concept and Patents

TIVM New Architecture (TIVM DV) Uses Basic TIVM Configuration with Secondary Rotors Acting as Dynamic Valves Rather Than as Compression Chambers

Primary Rotors and Vanes Now Perform Both Compression and Expansion

Eliminates Transfer of Significant Work Through the Sliding Vane Interface, and Thus the Major Source of Friction.

Significantly Reduces Pressure Differential Across Air Leakage Paths – Eases Sealing Challenge

Simplifies Porting Design – Provides Generous Flow Area

Simplifies Thermal Management

Simplifies Fabrication – Reduces Cost Challenge
New TIVM Design Concept and Patents

Patent Applications Submitted:
10/744230 and 10/744229
On December 22, 2003
New TIVM Design Concept and Patents

TIVM DV C/E Prototype is Being Fabricated for Testing in Third Quarter of GFY 2004

Uses “layer cake” rather than “pie segment” housings
Rigorous Meshing Surface Mathematical Solution

New Surface Solution Provides Vane Interface Gaps Well Less Than 0.001” Across Complete Meshing Surface
New Primary Vanes and Rotors for Generic Prototype Testing

New Vanes and Plastic Rotors Have Produced 3.9 atm Pressure with No Seals In Generic Prototype at 1000 RPM
Initial Test Data with New Surface Solution Vanes Without Seals

Compressor PSIG vs. Speed, rpm graph showing:
- New Vanes with a blue line and diamond markers
- Old Vanes with a green line and triangle markers

The graph indicates a positive correlation between speed and compressor pressure for both new and old vanes.
Rotating Seal Test Machine

Rotating Seal Test Machine Features

- Designed for Development of Primary and Secondary Rotor Seals
- Preserves Dimensional Scale of 80 kW TIVM / CE
- Leverages Existing Test Stand Hardware and Instrumentation
- Fast Turn Around Time for Test Specimens
- Dynamic Sealing at Operating Speed
- Gas Pressure Transducer
- Preload Load Cell
- Seal Friction via Torque Meter

Candidate Face Seal
Detailed Structural and Thermal Analysis of TIVM C/E Prototype Design is in Process

Example of Thermal Analysis for Differential Expansion
SLA Parts Have Been Fabricated and Used for Design and Fabrication Refinement
Prototype Compressor/Expander Metal Parts
## Expected Performance Matrix for TIVM Compressor/Expander

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<th>Requirement</th>
<th>Value</th>
<th>Comment</th>
<th>Expected</th>
</tr>
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<tbody>
<tr>
<td>Flow</td>
<td>91g/s For 80 kWe</td>
<td>Flow consistent with design flow demonstrated with temporary seals - as expected for positive displacement device</td>
<td>Designing for 100 g/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>2.5 atm</td>
<td>3.5 atm pressure demonstrated with temporary seals - as expected for positive displacement device</td>
<td>Capability Beyond Requirement</td>
</tr>
<tr>
<td>Power</td>
<td>5.8 kW</td>
<td>Key remaining performance issue – requires low friction effective seals</td>
<td>&lt;5.5 kW - Remains to be Demonstrated</td>
</tr>
<tr>
<td>Size</td>
<td>15 liters</td>
<td>Acceptable to car makers and OEMs</td>
<td>20-25 liters Acceptable</td>
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</tr>
<tr>
<td>Noise</td>
<td>&lt;65 db</td>
<td>Use of polymer parts and compliant seals will mitigate</td>
<td>To Be Demonstrated</td>
</tr>
<tr>
<td>Cost</td>
<td>$400</td>
<td>Cost estimates based on vendor quotes Give several $100’s in high volume</td>
<td>Expected to be acceptable</td>
</tr>
</tbody>
</table>
Interactions and Collaborations

- Mechanology has completed due diligence and negotiations and has entered into a development contract to introduce an industrial TIVM product into a substantial existing market in the near term.
- This provides independent conformation of the TIVM technology and provides manufacturing and distribution capability.
- DOE’s funding of Mechanology and the TIVM technology is paying off as a high leverage investment leading to many valuable energy sector products in addition to a successful automotive fuel cell compressor/expander/motor component.
Hardware Fabrication and Testing Plans

Use Rotary Seal Test Rig to Select Face Seals and Measure Performance – May 2004

Complete Fabrication and Initiate Testing of TIVM DV Prototype with Complete Set of Seals - Third Quarter GFY 2004

Refine TIVM DV Prototype Details Based on Test Results to Optimize Performance

Engage Subcontractor for Motor Design, Fabrication, Testing

Begin TIVM DV CEM Prototype Fabrication with Integrated Motor Fourth Quarter GFY 2004

Complete TIVM DV CEM Fabrication Second Quarter GFY 2005

Test CEM at Mechanology Third Quarter GFY 2005

Deliver TIVM DV CEM to DOE Fourth Quarter GFY 2005 – On Schedule