2013 DOE Hydrogen and Fuel Cells Program Review

Project ID: FC103

Roots Air Management System with Integrated Expander

Principal Investigator: Dale Stretch
Eaton Corporation
May 14, 2013

Overview

Timeline

- Project Start Date: 07/05/2012
- Project End Date: 07/04/2015
- % Complete: 25%

Budget Period	Start Date	End Date
1	07/05/2012	07/04/2013
2	07/05/2013	07/04/2014
3	07/05/2014	07/04/2015

Budget

- Total Project: $2,627,041
  - DOE Share: $2,101,630
  - Cost Share: $525,411
- Funds Obligated: $2,101,630
  - Funding received in FY12: $665,226
  - Funding for FY13: $821,776

Barriers & Technical Targets:

- Air management system drive cycle efficiencies, power & cost
- Cost Target: 2017 = $500
- Input Power at Idle = 200 W_e
- Compressor/expander efficiency @ 25% flow > 65/70%
- Motor/motor controller efficiency @ full flow > 90%
- Compressor/expander input power @ full flow < 8/14kW

Partners

- Prime: Eaton Corporation
- Subcontractors
  - Ballard Power Systems
  - Kettering University
  - Electricore, Inc.
- Technical Support
  - Argonne National Lab
  - Strategic Analysis

Relevance

Primary Objectives

- Demonstrate key improvements to compressor/expander efficiency, including:
  - Compressor/expander efficiency at 25% flow of >65/70% by 2017 (baseline = 62/64%)
  - Combined motor/controller efficiency at full flow of >90% by 2017 (baseline = 80%)
  - Compressor/expander input power at full flow of <8/14 kW by 2017 (base = 11/17 kW)

Secondary Objectives

- Conduct a cost reduction analysis, 2014 goal is to achieve $700 cost
- A fully tested and validated (TRL 6) air management system hardware capable of meeting 2017 Project Targets shown in table by project conclusion

Barriers

- Cost: Reduce by ~50%
- Performance: Reduce power by ~30%
- Motor Efficiency: Increase by ~40%
- Compressor Efficiency: Increase by ~5%
- Expander Efficiency: Increase by ~9%

Characteristic	Units	2011 Status	DOE Target 2017
Input power [a] at full flow [b], (with expander/without expander)	kW_e	11.0 / 17.3	8 / 14
Combined motor & motor controller efficiency at full flow [b]	%	80	90
Compressor / expander efficiency at full flow (C/E only) [b]	%	71 / 73	75 / 80
Input power at 25% flow [c] (with expander/without expander)	kW_e	2.3 / 3.3	1.0 / 2.0
Combined motor & motor controller efficiency at 25% flow [c]	%	57	80
Compressor / expander efficiency at 25% flow [c]	%	62 / 64	65 / 70
Input power at idle [d] (with / without expander)	W_e	600 / 765	200 / 200
Combined motor / motor controller efficiency at idle [d]	%	35	70
Compressor / expander efficiency at idle [d]	%	61 / 59	60 / 60
Turndown ratio (max/min flow rate)		20	20
Noise at maximum flow (excluding air flow noise @ air inlet & exhaust)	dB(A)	–	65
Transient time for 10 - 90% of maximum airflow	sec	1	1
System volume [e]	liters	15	15
System weight [e]	kg	22	15
System cost [f]	$	960	500

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Approach

For PEM fuel cells to achieve acceptance in the vehicle market, ***cost and reliability challenges must be met***

- The air supply sub-system has these requirements, plus it has to be efficient
- Current systems have trouble meeting all these objectives
- One reason is due to the high cost & complexity of air bearings used on competing air supply systems
- Second reason is the major challenge of air bearing systems meeting the needed efficiency and durability at 25% flow operation

This project will overcome these barriers by ***leveraging recent advancements to, and further develop, the Roots blower by:***

- Leveraging the broad efficiency map of Eaton's TVS compressor to improve the overall drive cycle fuel economy
- Integrating the expander, compressor and motor to reduce system cost and increase system efficiency (new approach, similar to a traditional turbocharger)
- Reducing part count, thus cost, by incorporating overhung expander and motor rotors such that 4 bearings and 2 shafts are used
- Operating at lower speed to leverage lower cost bearings and improve system reliability
- Developing a net shape plastic expander to lower manufacturing costs

Approach – Budget Period 1

Develop Compressor/Expander with Integrated Motor

- Developing CFD capability to accurately model roots compressors & expanders which gives the ability to model many designs to more quickly meet performance and efficiency targets
- Design & build a roots blower mule to be used to ascertain the optimized expander & compressor inlet, outlet and unit size more quickly and with less full hardware builds
- Argonne National Lab will model and analyze compressor and expander performance data and Ballard's FC module data to determine the optimal compressor expander combination to maximize FC module performance
- <u>Optimize compressor</u>
  - ✓ CFD modeling used to optimize compressor inlet, and outlet – optimize performance & efficiency
  - ✓ Performance data supplied to ANL to optimize compressor
  - ✓ Test various compressor configurations to optimize unit for application
- <u>Optimize expander</u>
  - ✓ CFD modeling used to optimize expander inlet, and outlet – optimize performance, efficiency and unit size
  - ✓ Performance data supplied to ANL to optimize expander
  - ✓ Test various expander configurations to optimize unit for application

Approach – Budget Period 1 con't, 2 & 3

Period 1 – Continued

- Develop compressor/expander assembly with integrated motor – drive for reduced cost
  - ✓ Design integrated system combines the expander, compressor and motor components to minimize complexity and number of components
  - ✓ Integrated design incorporates overhung expander and motor rotors into the design such that only four bearings and two shafts are used
  - ✓ To reduce cost, net shape plastic expander housing and rotors will be developed
  - ✓ Design other plastic air system components where applicable and feasible i.e. motor cooling jacket and motor end cover

Period 2 – Subsystem validation

- ✓ Prototype Compressor/Expander with Integrated Motor
- ✓ Compressor/Expander with Integrated Motor Performance and Validation Testing at Eaton

Period 3 - Validation Testing of System on 80kW FC Module

- Demonstration of roots based air system performance within the overall Hydrogen and Fuel Cells Application
  - ✓ Design & prototype complete system with integrated Ballard FC Stack
  - ✓ Compressor/Expander Validation Testing on Ballard Module
  - ✓ Correlate test results to ANL FC model
  - ✓ Determine Production Cost Estimates based on final design

Approach
Deliverables & Milestones

Deliverable 1.0	Project kick-off presentation with revised project management plan	**07/17/2012**
Deliverable 2.0	Concept design of the compressor/expander assembly with integrated motor	**07/03/2013**
1st DOE Rev.	**Project review with DOE & evaluate GO/NO-GO Criteria**	**07/05/2013**
Deliverable 3.0	Final prototype design of the compressor/expander assembly with integrated motor	**01/04/2014**
Deliverable 4.0	Compressor/expander validation test plan	**01/04/2014**
Deliverable 5.0	Compressor/expander validation test report	**07/04/2014**
Deliverable 6.0	OEM Integration and Test Plan	**07/04/2014**
2nd DOE Rev.	**Project review with DOE & evaluate GO/NO-GO Criteria**	**07/04/2014**
Deliverable 7.0	OEM validation test report	**04/04/2015**
Deliverable 8.0	Validated air management hardware	**06/04/2015**
Deliverable 9.0	System cost and manufacturability study	**07/04/2015**
Deliverable 10.0	Final Report and Presentation	**07/04/2015**

Accomplishments and Progress

Summary

Optimize Compressor

- Compressor Test Results: Baseline testing has been completed
- Inlet & Outlet CFD: In progress

Optimize Expander

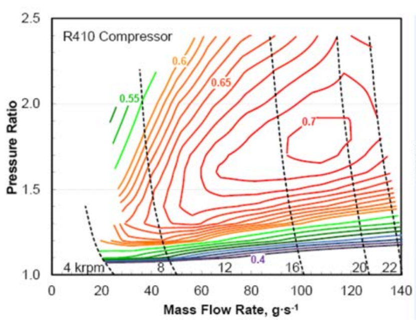
- Inlet & Outlet CFD: Meshing & iterative analysis in process
- Expander Test Stand: Test cell completed and operational, relative humidity and expander inlet temperature control was added
- Expander Test Results: 3 expander units and 8 different inlet configurations have been tested to improve efficiency
- Expander Plastic Rotor Analysis: Design of plastic rotors with integrated aluminum support structure was completed

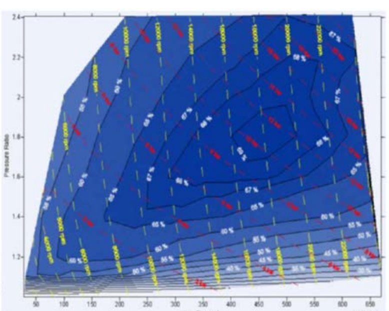
Develop Compressor/Expander Assembly with Integrated Motor

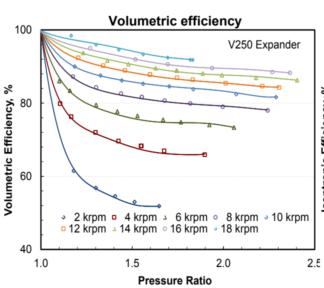
- Rotor Critical Speed Analysis: Initial model meshing completed, boundary conditions set with first frequency analysis finished
- Fuel Cell System Modeling: ANL has successfully updated its compressor and expander models with Eaton current product compressor and expander data

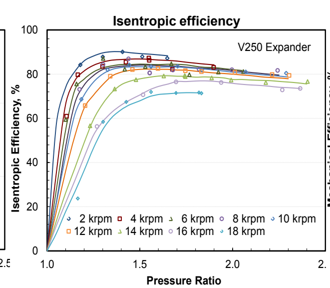
Accomplishments and Progress

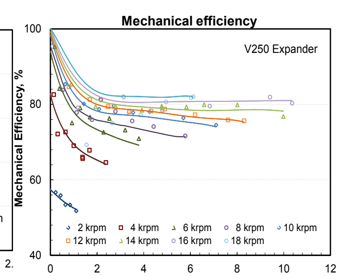
- Eaton provided ANL with compressor, expander and motor maps to incorporate into their system model
  - The compressor map show a close correlation between Eaton's performance data and ANL's modeling data, confirming ANL's model
  - ANL is in process of incorporating Eaton's expander & motor maps into its model

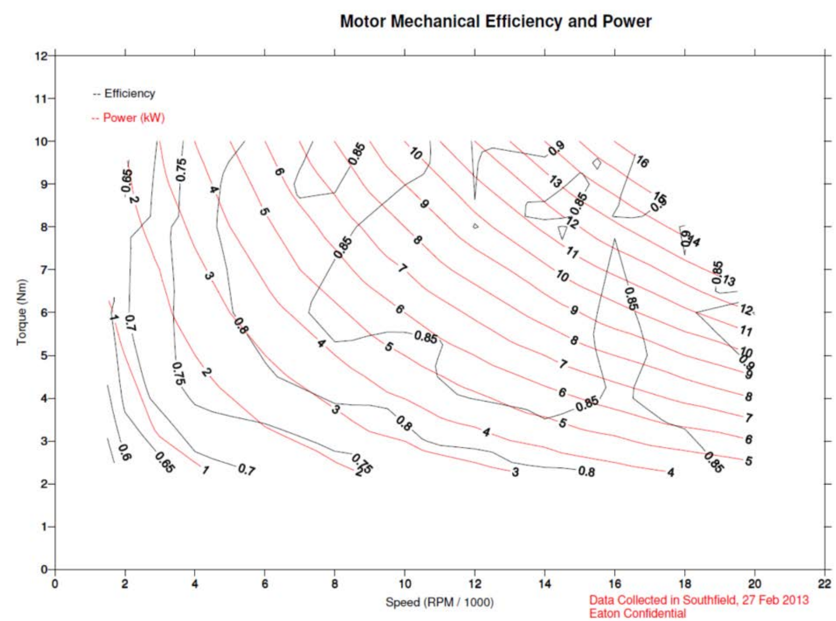






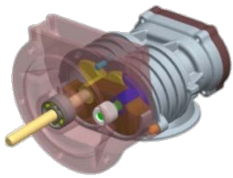


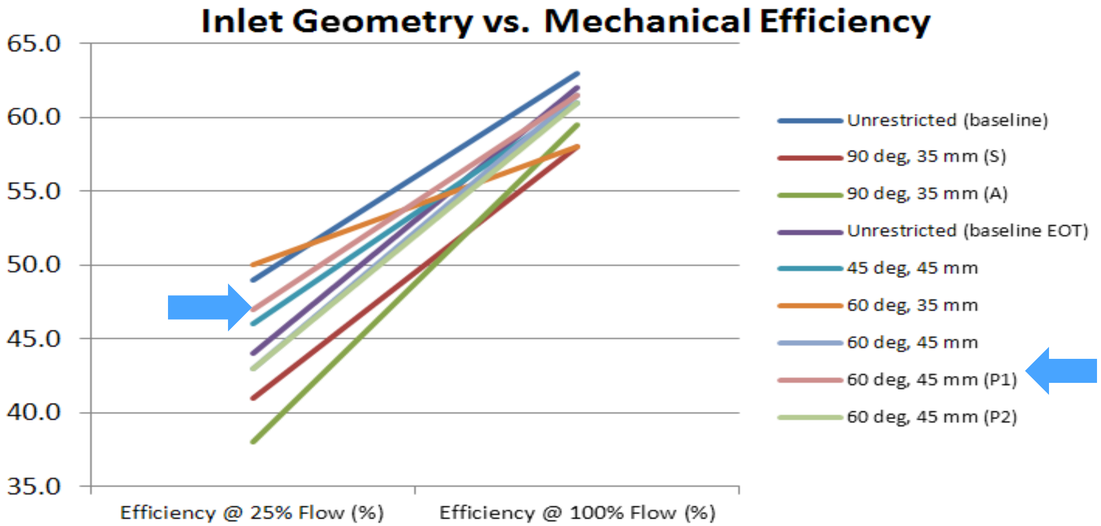


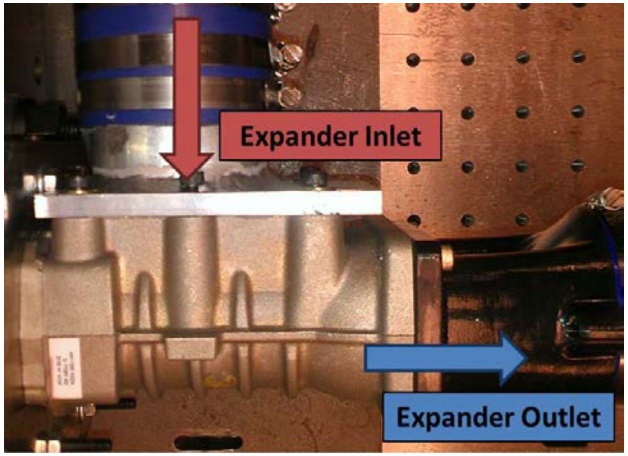


Accomplishments and Progress
Expander Experimental Test Results

- Tested 3 expanders: 1) R200, 2) V250 Gen 2 and 3) V250 Gen 1 to optimize expander efficiency, baseline testing indicated
  - V250 Gen 2 was better at 25% flow rate but the V250 Gen 1 was better at 100% flow rate, This led us to conclude the rotors in gen 2 were better than gen 1. Therefore, the improved rotor geometry of the V250 Gen 2 will be considered for the final expander design
  - The V250 Gen 1 had the best overall performance, therefore additional testing was focused on this expander
- Additional testing on the V250 Gen 1
  - 8 inlet geometries were tested by varying inside diameter, angle and flow direction
  - Optimal inlet angle and diameter have been found for this configuration
- Next Steps: Testing will continue in order to improve overall air movement and efficiency







R200 with Pressurized Outlet

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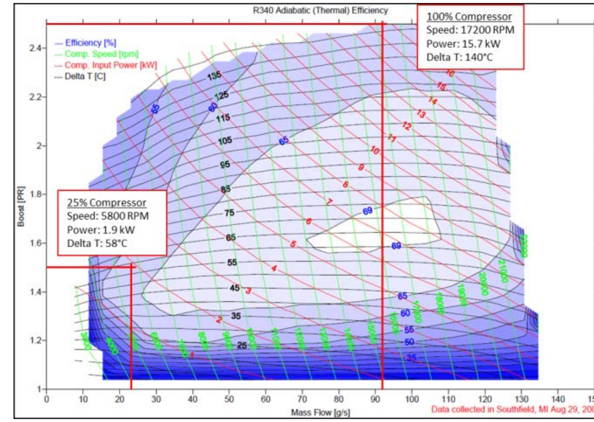
Accomplishments and Progress

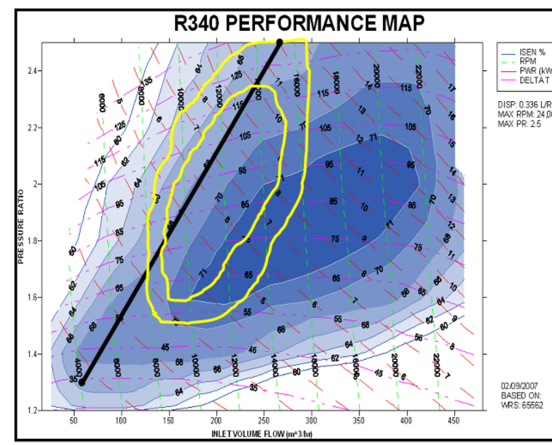
Optimizing Compressor Performance

Progress to date

- Created experimental compressor R340 utilizing high efficiency Twin Vortices Series (TVS) Roots technology
- Tested R340 & V250 Gen 2 to create baseline performance maps
- Next Steps
  - Tuning of the roots compressor peak efficiency island to reduce peak power and air output temperature
  - Size and rotor configuration can be utilized to move the supercharger's peak efficiency island
  - Test new inlet/outlet port configurations to match the resultant flow vector, minimizing air flow restriction



R340 Compressor Map with DOE targets



Air Demand Operating Curve for the R340 TVS Roots Type Supercharger

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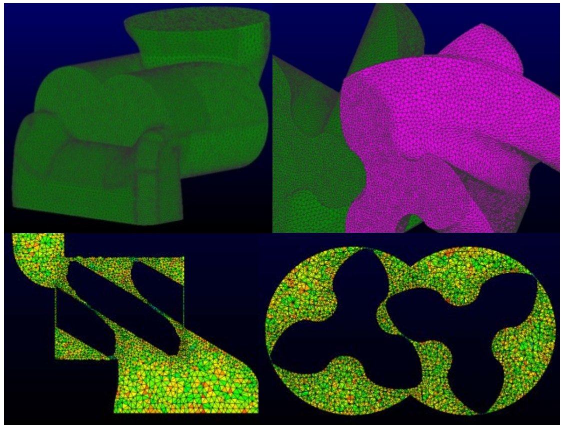
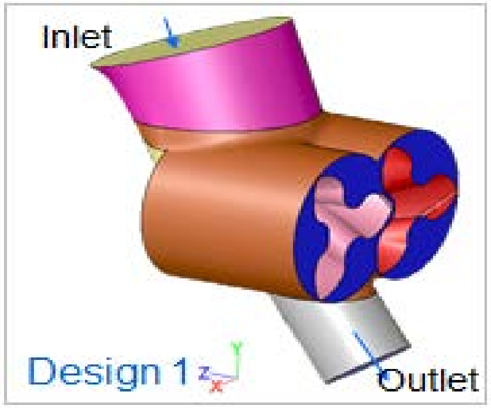
Accomplishments and Progress

Inlet Outlet Expander CFD (Kettering Progress)

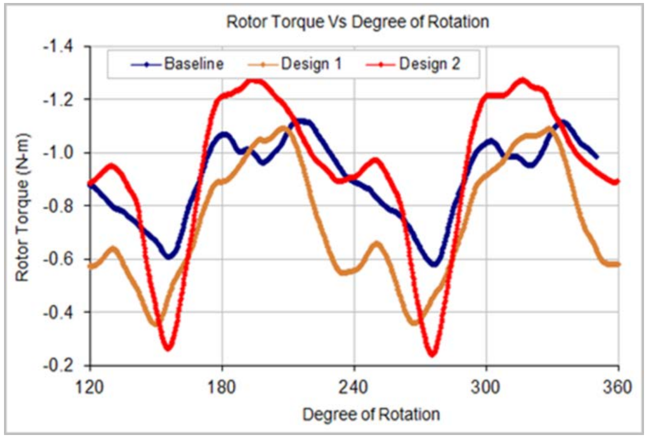
- Eaton has experience with compressor & expander CFD, however a highly refined model is required to accurately determine improvements to efficiency & performance
- Progress to date: Grid Mesh generation of the roots-expander geometry
    - Meshing was started using the STAR-CCM+ software but due to numerous distorted and skewed cells and limitation of the software to correct them this approach was shelved
    - 2nd attempt using POINTWISE was successfully completed using an overset meshing technique (creates individual mesh around each rotating object)
- Next step - CFD analysis of the air flow through the roots-expander



Mesh of the supercharger-expander



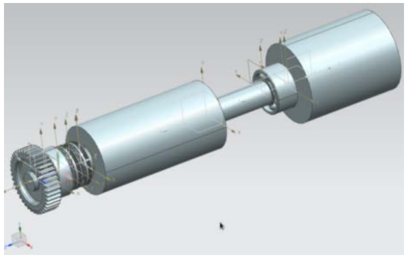
Supercharger meshed geometry



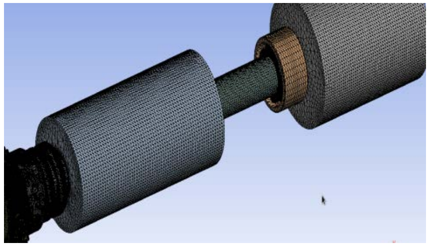
Example of Previous CFD Results

Accomplishments and Progress
Overhung Motor Rotor Critical Speed Analysis (Kettering)

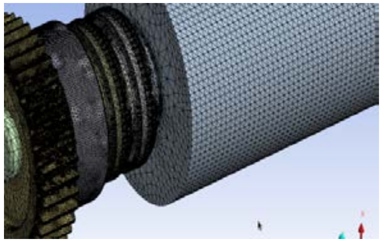
- An R340 roots compressor with integrated motor and overhung motor magnet has been analyzed for critical speed performance
- Progress to date:
  - Eaton generated CAD model with rotors modeled as cylinders with the same mechanical properties for simplicity
  - Grid generation of the rotor assembly has been completed and the meshed model as shown
  - Compressor and motor speed results completed to validate to modeling ability
- Next step – Model compressor, expander and motor as a system



CAD Model of rotor-shaft assembly



Overall view of the meshed rotor-shaft assembly in ANSYS



View of the meshed gear, left bearing, and sleeves

Part Name	Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)
Gear	DIN EN 10083	205,000	0.30	7,861
Front Bearing	Steel	206,800	0.30	7,861
Rotor	SAE 6061	68,300	0.33	2,700
Shaft	A 1547	200,000	0.29	7,870
Rear Bearing	Steel	206,800	0.30	7,861
Sleeves	Steel	206,800	0.30	7,861
Magnet	Steel	206,800	0.30	19,650*

* Density of the magnet is considered to be 2.5 times of steel due to magnetic flux.

Material Properties of Rotor-shaft assembly

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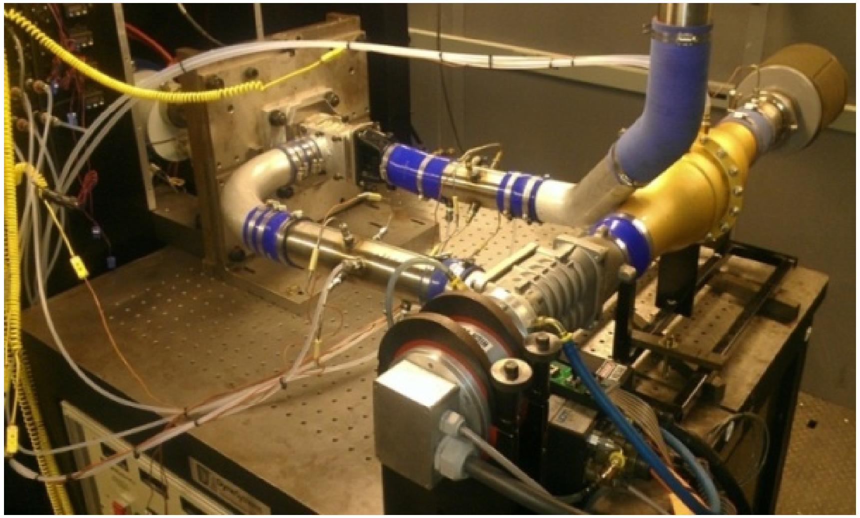
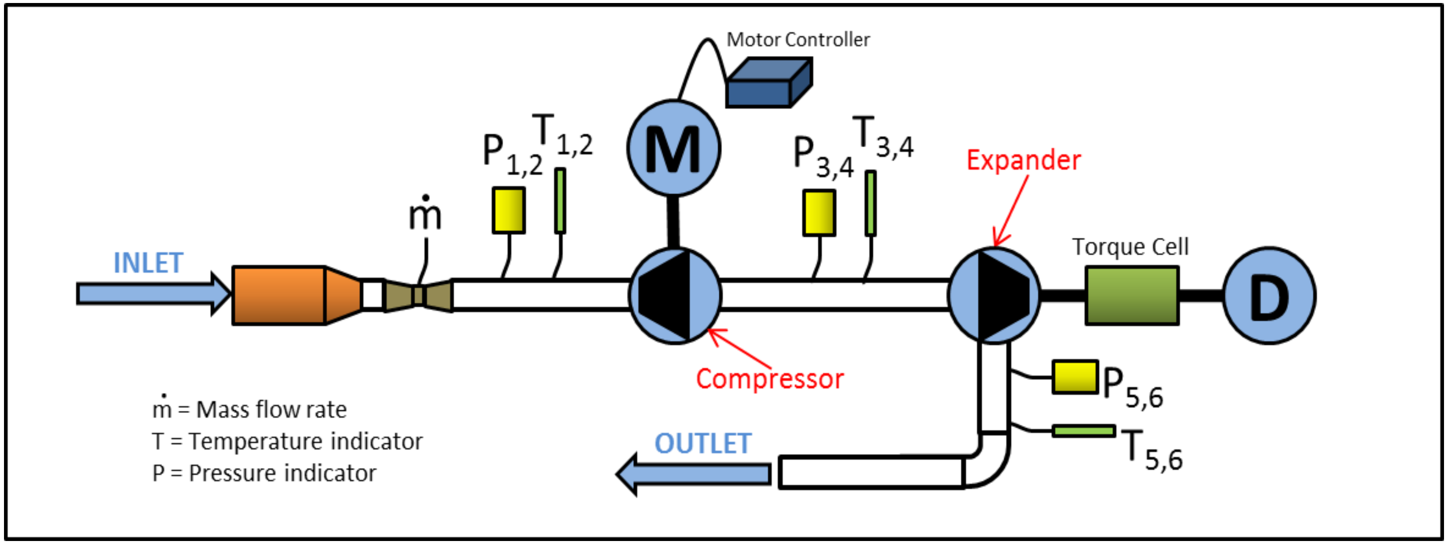
Accomplishments and Progress
Expander Test Stand (Eaton)

The test stand is operational

- Fuel Cell work required updates to Eaton's Supercharger Test Lab
- Relative humidity and inlet air temp controls were added to the test stand capability





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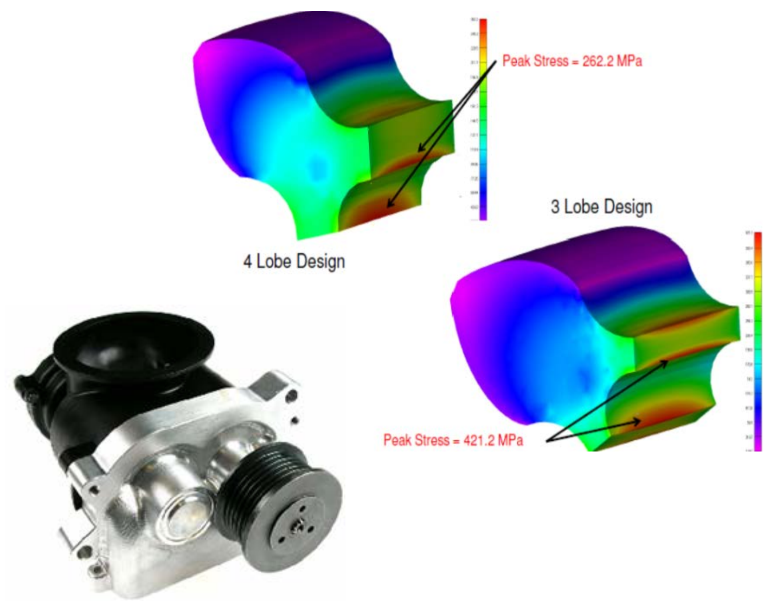
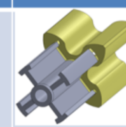
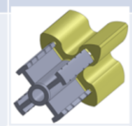
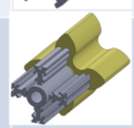
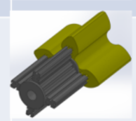
Accomplishments and Progress

Expander Plastic Rotor Analysis (Eaton)

- Low Fuel Cell outlet temperatures allow for the use of low cost plastic housings and rotors
- FEA indicated that the 4 lobe design has lower stresses than the 3 lobe design
    - 4 Lobe design still did not meet speed & stress requirements at operating temperature
- High stress due to speed & heat warranted aluminum support structure
    - Iterated to optimize design (see table)

Conclusion: Design iteration number four achieved 20,000 rpm although, the stresses exceeded the capability of the glass reinforced composite. At 70°C this design is considered acceptable.



Design Iteration	Comments		Speed Achieved (rpm)	Max Principal Stress of Composite (MPa)
1		Unable to run due to lack of mechanical features – composite separated from aluminum extrusion	N/A	179
2		addition of mechanical locking feature along length of lobe	8000	258
3		Dovetail interlock along diameter and at the tip of the root	12500	644
4		Reduced height of aluminum extrusion into the lobe; simplified geometry of dovetail	20,000	614

Summary of FEA results at 150°C

Collaborations

Ballard

Relationship: Industry Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Provide Fuel Cell OEM input into the design and specification of the air management system. Integrate, test and validate the Eaton compressor/expander with a 75kW Ballard HD6 stack.

Kettering

Relationship: University Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Provide critical analytical support includes expander CFD analysis, Critical Speed Analysis of compressor/expander design, and Critical Speed Analysis iterations of Eaton's compressor only

Electricore, Inc.

Relationship: Industry Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Administrative Program Management

Argonne National Lab

Relationship: Federal Laboratory Sub-contractor outside DOE Hydrogen and Fuel Cells Program

Responsibility: Provide critical simulation and modeling support of the fuel cell system to assist in optimizing the roots air system with the Ballard HD6 module

Strategic Analysis

Relationship: Industry Sub-contractor outside DOE Hydrogen and Fuel Cells Program

Responsibility: Develop fuel cell system cost utilizing manufacturing cost of roots based air management system.

Proposed Future Work

Period 1 – Items to complete by June 2013

- ANL model - Determine optimal compressor expander configuration
- Kettering CFD model – Optimize roots expander and compressor
- Design roots expander and compressor to meet performance and cost targets
- Design cost effective plastics expander
- Design and model integrated roots expander/compressor/motor
- Project review with DOE, report progress against GO/NO-GO Criteria

Period 2 – July 2013 to July 2014

- Prototype Compressor/Expander with Integrated Motor
  - Design, Detail, Fabricate & Qualify Prototype Components
  - Determine Production Cost Estimates
- Test Compressor/Expander with Integrated Motor at Eaton
- Project review with DOE, report progress against GO/NO-GO Criteria

Period 3 – July 2014 to July 2015

- Conduct Performance and Validation Testing at Ballard with integrated compressor expander on 80kW FC Module
- Project review with DOE, report progress against GO/NO-GO Criteria

Summary

Project Progress & Milestone Status

- Project is currently on schedule, all major and required documents have been created and submitted
- All project milestones have been met to date
- Project is on track to meet yearly Go, No Go criteria, project performance targets and deliverables

Technical Progress

- Expander CFD Analysis – Previously, some optimization was completed using FLEUNT software however, Kettering University has begun CFD analysis using STAR-CCM software to provide greater modeling accuracy.
- Expander Test Mule Design – Current performance data for both compressor and expander has been provided to ANL for input into the Fuel Cell System Model. Concurrently, Eaton analysis indicates a reduction in expander displacement, from the current V250 design, is necessary. Testing has begun to characterize the effect of reduced rotor size on expander performance.
- Plastic Expander Rotor – FEA predicts a substantial improvement in strength when utilizing a 4 lobe rotor over a 3 lobe rotor. Further analysis and design iterations are necessary to meet performance targets with a plastic rotor.

Summary Table

Progress Towards Project Targets

Characteristic	Units	2011 Status		2012+ Progress		2015 Target	2017 Target
Input power @ **full flow** , (with expander/without expander)	kW_e	11	17.3	11.6	15.9	8/14	8/14
Combined motor & motor controller efficiency @ **full flow**	%	80		92		90	90
Compressor / expander efficiency @ **full flow** (C/E only)	%	71	73	74	64	75 / 75	75/80
Input power @ **25% flow** (with expander/without expander)	kW_e	2.3	3.3	1.3	1.6	1.0/2.0	1.0/2.0
Combined motor & motor controller efficiency @ **25% flow**	%	57		70		80	80
Compressor / expander efficiency @ **25% flow**	%	62	64	65	64	65/70	65/70
Input power @ **idle** (with / without expander)	W_e	600	765	TBD		200/200	200/200
Combined motor / motor controller efficiency @ **idle**	%	35		TBD		?	70
Compressor / expander efficiency @ **idle**	%	61	59	TBD		60/60	60/60
Turndown ratio (max/min flow rate)		20		20		20	20
Noise @ **full flow** (excluding air flow noise at air inlet and exhaust)	dB	-		65[1]		65	65
Transient time for 10 - 90% of maximum airflow	sec	1		1[1]		1	1
System volume	liters	15		15[1]		15	15
System weight	kg	22		16[1]		15	15
System cost	$	960		TBD		500	500

Data taken at required temperature and humidity

1 – Test run prior to start of program, will be confirmed before end of program

Meets the goal (green)

Better than 2011 baseline but does not yet meet goal (blue)

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