V.G.3 Roots Air Management System with Integrated Expander

Dale Stretch (Primary Contact), William Eybergen, Brad Wright
Eaton Corporation
W126N7250 Flint Drive
Menomonee Falls, WI 53051-4404
Phone: (248) 226-6799
Email: DaleAStretch@Eaton.com

DOE Manager
Jason Marcinkoski
Phone: (202) 586-7466
Email: Jason.Marcinkoski@ee.doe.gov

Contract Number: DE-EE0005665

Subcontractors:
- Ballard Power Systems, Burnaby, BC, Canada
- Kettering University, Flint, MI
- Electricore, Inc., Valencia, CA

Project Start Date: July 5, 2012
Project End Date: July 4, 2015

Overall Objectives

Primary Objectives

- 62/64% (baseline 2011), >65/70% (target 2017), compressor/expander efficiency at 25% of full flow
- 80% (baseline 2011), >90% (target 2017), combined motor/motor controller efficiency full flow
- 11.0/17.3 kW (baseline2011), <8/14 kW (target2017), compressor/expander input power at 100% of full flow

Secondary Objectives

- Meeting all 2017 project target objectives in Table 1
- Conduct a cost reduction analysis to identify areas for additional possible cost reductions

A fully tested and validated TRL 7 air management system hardware capable of meeting the 2017 project targets in Table 1 will be delivered at the conclusion of this project.

Fiscal Year (FY) 2013 Objectives

- Tune the peak efficiency island of the compressor to best fit the primary objective of 14.0-kW input power @ 100% of full flow and 2.0-kW input power @ 25% of full flow.
- Design rotor configuration of the expander to optimize output power of the expander to best fit the primary objective of 6.0-kW input power @ 100% of full flow and 1.0-kW input power @ 25% of full flow.
- Develop compressor/expander and motor concept to meet the primary objective of 8.0-kW input power @ 100% of full flow and 1.0-kW input power @ 25% of full flow.
- Develop compressor and expander computational fluid dynamics (CFD) capability (demonstrate ability to model compressor case clearances of 40 µm and rotor clearance of 80 µm) and optimize the roots compressor and expander inlet, outlet and rotor geometry to position peak efficiency islands to maximize the performance of the cathode air system.
- Develop expander plastic rotors that meet the application requirements.
- Supply compressor and expander performance data and maps, Ballard 75-kW module data to Argon National Laboratory. The models will be used to determine the optimal compressor expander combination to maximize the Ballard FC module performance.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(B) Cost: Reduce by ~50%

(C) Performance
  - Reduce power by ~30%
  - Motor efficiency: increase by ~40%
  - Compressor efficiency: increase by ~5%
  - Expander efficiency: increase by ~9%

Technical Targets

A fully tested and validated TRL 6 air management system hardware capable of meeting the 2017 project targets in Table 1 delivered at project conclusion.

FY 2013 Accomplishments

Optimize Compressor

- Improved the compressor/expander test rig by adding relative humidity and inlet temperature control.
- Reduced the compressor power consumption on tested hardware from 15.6 kW to 14.7 kW by increasing the rotor helix angle.

TABLE 1. 2015 and 2017 Project Targets

Characteristic	Units	Current Status	Project Target 2015	DOE Target 2017
Input power[a] at full flow[b] (with expander/without expander)	kWe	9.9/13.8	8/14	8/14
Combined motor and motor controller efficiency at full flow[b]	%	90	90	90
Compressor/expander efficiency at full flow (compressor/ expander only)[b]	%	68/64	75/75	75/80
Input power at 25% flow[c] (with expander/without expander)	kWe	1.3/1.7	1.0/2.0	1.0/2.0
Combined motor and motor controller efficiency at 25% flow[c]	%	70	80	80
Compressor/expander efficiency at 25% flow[c]	%	61/70	65/70	65/70
Input power at idle[d] (with/without expander)	We	TBD/270	200/200	200/200
Combined motor/motor controller efficiency at idle[d]	%	TBD	?	70
Compressor/expander efficiency at idle[d]	%	TBD	60/60	60/60
Turndown ratio (max/min flow rate)		20	20	20
Noise at maximum flow (excluding air flow noise at air inlet and exhaust)	dB(A) at 1 meter	65 (with enclosure and suppression)	65 (with enclosure and suppression)	65
Transient time for 10-90% of maximum airflow	sec	1	1	1
System volume[e]	liters	15	15	15
System weight[e]	kg	16	15	15
System cost[f]	$	TBD	500	500

[a] Electrical input power to motor controller when bench testing fully integrated system. Fully integrated system includes control system electronics, air filter, and any additional air flow that may be used for cooling.

[b] Compressor: 92 g/s flow rate, 2.5 bar (absolute) discharge pressure; 40°C, 25% relative humidity (RH) inlet conditions. Expander: 88 g/s flow rate, 2.2 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[c] Compressor: 23 g/s flow rate, minimum 1.5 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 23 g/s flow rate, 1.4 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[d] Compressor: 4.6 g/s flow rate, minimum 1.2 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 4.6 g/s flow rate, <compressor discharge pressure, 70°C, 20% RH inlet conditions.

[e] Weight and volume include the motor, motor controller and system enclosure.

[f] Cost target based on a manufacturing volume of 500,000 units per year.

[g] DTI cost model of the Honeywell 100,000 rpm machine, 2.5 bar (absolute), 92 g/s, dry air, 40°C: $960 including markup. TIAX 2009 estimate of Honeywell technology (compressor, expander, motor, motor controller) presented at 2010 Annual Merit Review and Peer Evaluation: $790 including 15% markup.

TBD – to be determined

- Increased the compressor pressure ratio on tested hardware from 2.4 to 2.6 by increasing the rotor helix angle.
- Theoretically estimated the final compressor design to have a power consumption of 13.8 kW. This compressor is 38% smaller than the compressor tested where 14.7 kW was achieved.

Optimize Expander

- Increased the expander power production on tested hardware from 3.2 kW to 3.5 kW by the addition of a diverter on the inlet port.
- Determined the optimal inlet port angle, for power production, on the tested expander. The 60 deg inlet angle had a 0.3 kW greater power than the 90 deg (which was the worst performer).
- Increased the expander pressure ratio on tested hardware from 1.6 to 1.75 by optimizing the inlet port diverter shape.
- Theoretically estimated the final expander design to have a power production of 3.9 kW.

Develop Compressor/Expander Assembly with Integrated Motor

- Created layout of expander, compressor and motor integrated system that optimized the system performance but minimized bearing and gear part count. Current part count of major components is 35 which include 10 bearings and seven gears.
- Designed and analytically optimized plastic rotors to meet speed and load requirement. Final design with aluminum insert can spin up to 20,000 rpm @ 150ºC. This is sufficient for all operating conditions the expander will experience.
- Designed plastic rotor mold and determined porting that would optimize the root fiber content.
- Worked with Argonne National Laboratory to develop roots compressor and expander models for Period 2 fuel cell system modeling optimization. Validated their models with empirical data.

Modeling

- Improved the ability to more accurately model Roots expanders and compressors by reducing the model tip to root and tip to wall clearances. Clearances were reduced from 600 µm to <100 µm, a six-fold reduction. This will provide a more accurate optimization tool for optimizing the compressor and expander inlet and outlet and root geometries.

✧ ✧ ✧ ✧ ✧

INTRODUCTION

Proton exchange membrane (PEM) fuel cells remain an emerging technology in the vehicle market with several cost and reliability challenges that must be overcome in order to increase market penetration and acceptance. The DOE has identified the lack of a cost-effective, reliable, and efficient air supply system that meet the operational requirements of a pressurized PEM 80-kW fuel cell are some of the major technological barriers that must be overcome. This project will leverage roots blower advancements and develop and demonstrate an efficient and low-cost fuel cell air management system. Eaton will build upon our newly developed P-Series roots blower and shift the peak efficiency making it ideal for use on an 80-kW PEM module. Advantages to this solution include:

- Lower speed of the roots blower eliminates complex air bearings present on other systems.
- Broad efficiency map of roots systems provide an overall higher drive cycle fuel economy.
- Core roots machine technology has been developed and validated for other transportation applications.

Eaton will modify their novel R340 Twin Vortices Series (TVS) roots-type supercharger for this application. The TVS delivers more power and better fuel economy in a smaller package as compared to other supercharger technologies. By properly matching the helix angle with the rotor's physical aspect ratio the supercharger's peak efficiency can be moved to the operating range where it is most beneficial for the application. The compressor will be designed to meet the 92 g/s flow at a pressure ratio of 2.5, similar in design to the R-Series 340. A net shape plastic expander housing with integrated motor and compressor will significantly reduce the cost of the system.

APPROACH

The approach will be to leverage recent advancements to and further develop roots compressor and expander technology by leveraging the broad efficiency map of Eaton's TVS compressor to improve the overall fuel cell drive cycle fuel economy. In Period 1, the project will optimize the expander and compressor individually at the specified requirements, with an integrated expander, compressor and motor concept as the final deliverable. The primary goal will be meet the power and efficiency objects. The secondary objective is to reduce subsystem cost by keeping part count low by developing a net shape plastic expander housing and rotor. This work will be supplemented with CFD analysis to help optimize the expander and compressor performance and system analysis which will help optimize the integrated system

Period 2 will finalize the integrated concept, then build and test the integrated system and individual subsystems. The last phase (3) will be to incorporate the roots air management system with integrated expander into an overall hydrogen and fuel cells application. This will include designing, building and testing the complete system.

RESULTS

The team continued to development the compressor, expander and finalized the system concept using both experimental and analytical methods in the last three months.

Inlet Outlet Expander CFD

This last quarter improvements were made on the CFD modeling capability. CFD analysis of the supercharger-expander with 300-µm gap width clearances using the STAR-CCM+ software were achieved in the first quarter of this year, but calculations of torque did not correlate very well with the experimental data so refinement to the gap clearances was pursued. This pursuit proved to be difficult because the smaller gap width need for better accuracy cause the "off the shelf" available software to crash during the mesh generation process. Hence, it was decided to acquire specialized software that would generate a refined mesh and not crash during analysis. Results show that the rotor torque correlation is more accurate. Additional work is needed on the flow correlation, but this is believed to be a much easier problem to solve by using a more refined mesh and by adjusting some of the input parameters.

Expander Test Stand

Inlet air temperature control was added to the test stand, by using an air-to-liquid heat exchanger and by incorporating controlled temperature conditioning equipment. Relative humidity control was added to the airflow stream via pulse width modulated solenoid injector and a high-pressure pump.

Expander Test Results

An expander with the highest efficiency possible and meet DOE power and efficiency targets, lessons learned from testing were as follows. The direction of rotation has been determined through testing existing compressor designs as expanders with forward and reverse rotations. Reverse rotation, opposite of compressor rotation, consistently produces 5-10% improvement over a standard rotation arrangement. A multitude of inlet variations have been tested with a 60°, measured from perpendicular to rotor axis, inlet produces the best results. The 60° inlet will also contain optimized diverter geometry to shift the peak efficiency island toward the expander's operating targets. The inlet must be a minimum of 45-mm inside diameter to support a 250 cc expander displacement. The V250 Gen 2 rotors feature an increased root radius and provide increased efficiency over the Gen 1 rotors by eliminating a leak path from the rotor's root to the bearing bore. The optimized V250 expander will incorporate these parameters with input from the CFD model to create the V250 optimized expander. Performance estimates for the V250, optimized to DOE specifications, are 0.38 kW @ 25% full flow and 3.98 kW @ 100% full flow.

Compressor Test Results

The optimized compressor will leverage both P400 and R340 designs to create a reduced displacement, high helix angle compressor capable of 2.5 pressure ratio with power consumption under the DOE target of 14 kW. The increased helix angle of the P400 allowed the unit to reach pressure ratios over 2.6 without exceeding the temperature limits of the compressor. The increased helix angle of the P400 rotor, when applied to the R340 rotor, will reduce its overall length and displacement creating a high helix angle compressor with a displacement of 260cc/rev named P260. This change will increase the operating speed of the compressor and shift the 25% full flow and 100% full flow operating points towards the peak efficiency island. Performance estimates for the P260 compressor, at DOE specified conditions, should be 1.7 kW @ 25% full flow and 13.8 kW @ 100% full flow.

Develop Compressor/Expander with Integrated Motor

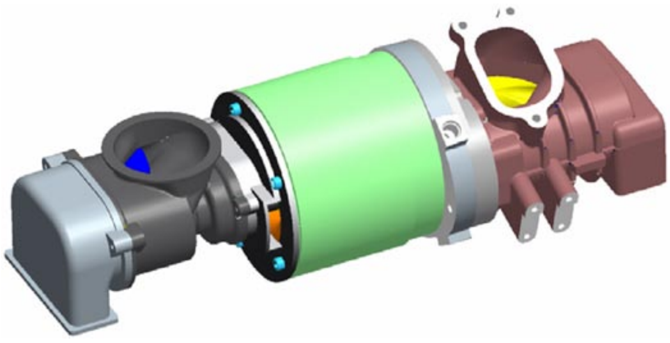


FIGURE 1. Fuel Cell Air System (Expander/Motor/Compressor)

The system concept design, Figure 1, consists of an expander coupled to a motor through a gear ratio, and a compressor directly coupled to the opposite side of the motor. This configuration, instead of a non-geared direct drive design, is driven by the need to operate the compressor and expander at their individual optimized speeds, which are not the same. Testing to date has shown that to optimize the complete system, a gear ratio between 1.7 and 3.0 is needed. The final ratio will be determined when the final compressor and expander testing is complete.

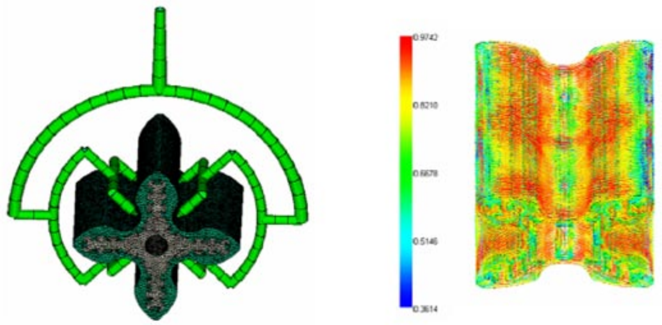
System performance utilizing exisiting hardware, a P400 compressor and V250 expander, is estimated to be 1.4 kW at 25% full flow and 10.9 kW at 100% full flow. After changing to an optimized compressor and expander combination, a P260 compressor and V250 optimzed expander, estimated system performance is 1.3 kW at 25% full flow and 9.9 kW at 100% full flow, Table 2.

Expander Plastic Rotor

The runner system for the rotor injector mold was optimized through mold flow simulation. Initial design was a pin gate located at the tip of each of the four lobes. Fibers were highly oriented at the gate location on the lobe tip and became increasingly more random towards the root. In an effort to increase fiber orientation at the root, and thereby increase the root strength, a second runner system was designed and evaluated. The final design has a runner system with eight pin gates that are located in the root at two points. The resulting fiber orientation increased the alignment in the root region with random fiber orientation at the tip. The 8-pin runner system was implemented into the final tool design and tool fabrication has been started.

TABLE 2. Predicted P260 Compressor, V250 Optimized System Performance

Predicted System Performance at DOE Conditions					
Unit		25% Target		100% Target	
		Power	System Pwr	Power	System Pwr
		kW	kW	kW	kW
Compressor	P260	1.67	**1.30**	13.8	**9.9**
Expander	V250 Opt	-0.38		-3.98	



Red = highly oriented and Blue = random

FIGURE 2. 8-Pin Runner System and Fiber Orientation

CONCLUSIONS AND FUTURE DIRECTIONS

Period 1 Conclusions

Delivered concept design of the compressor/expander assembly with integrated motor that projected to meet the project performance targets of:

Full Flow Conditions

- Input power (with expander) projected to be 9.9 kW not 8 kW
- Input power (with expander and heat recovery) projected to be 9.4 kW not 8 kW
- Input power (without expander) projected to meet 13.8 kW vs 14 kW
- Motor plus motor controller efficiency projected to meet 90%

25% Flow Conditions

- Input power (with expander) projected to be 1.3 kW not 1 kW
- Input power (with expander and heat recovery) projected to be 1.2 kW not 1 kW
- Input power (without expander) projected to meet 1.7 kW vs. 2 kW
- Motor plus motor controller efficiency projected to be 70% not 80%

Idle Flow Conditions

- Input power (with expander) to be determined
- Input power (without expander) projected to be 270 W not 200 W
- Motor + motor controller efficiency to be determined

Future Directions

- Prototype Eaton compressor/expander with integrated motor:
  - Finalize detail drawing package and release for fabrication
  - Procure prototype components
  - Inspect, assemble, debug prototypes to verify functionality
  - Develop production cost estimates
  - Document volume production cost model and identify opportunities, design and process changes that will improve cost
- Design, build, procure and debug Eaton performance stand test rig
- Conduct performance and validation testing at Eaton:
  - Write test plan/determine test criteria
  - Measure and document using maps and excel data sheets
  - Conduct test at the specified target conditions
  - Document results with performance maps
  - Measure system weight and system volume including motor, controller, and system enclosure

FY 2013 PRESENTATIONS

1. Eybergen, Bill, Roots Air Management System with Integrated Expander, U.S. DRIVE Technical Meetings - Fuel Cell Tech Team (FCTT), December 19, 2012.

2. Stretch, Dale, Roots Air Management System with Integrated Expander, DOE Merit Review - Fuel Cell Tech Team (FCTT), May 14, 2013.