V.D.1 Roots Air Management System with Integrated Expander

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Subcontractors

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

Project Start Date: July 5, 2012
Project End Date: December 31, 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 (baseline 2011) < 8/14 kW (target 2017) 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 technology readiness level (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) 2015 Objectives

- Complete plastic expander rotors development and final assessment of Eaton's all plastic expander
- Complete performance and validation testing on the complete air system per predefined test plan approved by DOE
- Baseline Ballard HD7 fuel cell as benchmark for assessing Eaton's Air Management System
- Assess the performance capability of Eaton's Air Management System on Ballard HD7 fuel cell per predefined test plan approved by the DOE
- Provide system test data for Argonne National Laboratory for model development and verification
- Document Eaton's Air Management System performance capability in test report

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

At the conclusion of this project, a fully tested and validated TRL 6 air management system hardware capable of meeting the 2017 project targets in Table 1 will be delivered.

FY 2015 Accomplishments

- End of Period 2 Conclusions
  - Delivered final prototype of the compressor/expander assembly with integrated motor
  - Delivered compressor/expander validation test report which included expander, motor and compressor, wet and dry maps, system maps, and acceleration and acoustic noise test results
  - Successfully demonstrated twisted plastic rotors in compressor and expander environment
  - Worked on developing a high compression ratio (3.0) roots compressor with minimal efficiency losses using low thermal growth material; fabrication process prevented complete evaluation; many

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 & motor controller efficiency at full flow[b]	%	90	90	90
Compressor/expander efficiency at full flow (C/E 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 & 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 idled (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 & suppression)	65 (with enclosure & 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% 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, LLC 2009 estimate of Honeywell technology (compressor, expander, motor, motor controller) presented at 2010 Annual Merit Review and Peer Evaluation: $790 including 15% markup.
RH—relative humidity; TBD - to be determined

lessons learned on how to fabricate correctly; second attempt will have a much higher level of success

- Beginning of Period 3 Conclusions
  - Built and tested two sets of Eaton's Air Management Systems for Ballard testing
  - Experimented with injecting water at the compressor inlet Eaton's Air Management System as a potential replacement to the fuel cell humidifier
  - Baselined the HD7 system using the existing air system for comparison to Eaton's Air Management System

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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. Some of the major technological barriers that must be overcome include DOE's identification of the lack of a cost effective, reliable, and efficient air supply system that meets the operational requirements of a pressurized PEM 80-kW fuel cell. 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 the following.

- 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 its 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 development of, 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 is to meet the power and efficiency objectives. 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 computational fluid dynamics 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, Period 3, will be to incorporate the Roots Air Management System (AMS) with integrated expander into a hydrogen fuel cell application. This will include designing, building, and testing the complete system.

RESULTS

In the first half of 2014 the team designed and built the finalized compressor/expander air system concept. The remainder of 2014 validated the hardware through a series of tests. The test plan consisted of seven different performance tests conducted on the AMS with two of the tests run on Eaton's relative humidity dynamometer. The performance tests are as follows:

- Expander Component Test
- Motor Component Test
- Compressor Component Test
- Expander + Motor Sub-System Testing
- Dynamometer + Motor + Compressor Full-System Testing
- Noise Testing on Full-System
- Transient Time Testing on Full-System

Table 2 summarizes how Eaton's AMS (Eaton Test Results) has met the project target objectives laid out by DOE at the beginning of the project. The table presents all the criteria given in DOE's Table 1. The objective barriers (second to last column of data) are the percent improvements requested by DOE ([2015 Target – 2011 Baseline]/2011 Baseline). The barriers the Eaton AMS achieved (last column) are the percent improvements Eaton actually achieved with the AMS ([Eaton Test Results – 2011 Baseline]/2011 Baseline). The achieved numbers presents how well Eaton's AMS has improved on the 2011 air system. These values can be compared to the DOE objectives to see how well the Eaton system has improved its air management system technology.

The following conclusions can be drawn from the testing of Eaton's AMS (Table 2).

- Although the 100% and idle compressor power have not achieved the targeted value, there have been improvements compared to the 2011 numbers.
- The low and mid-range power numbers have improved significantly in comparison to the 2011 numbers with the 25% flow point exceeding the target amount.
- The roots expander published efficiencies are lower than centrifugal expander efficiencies. This is partially attributed to the way roots efficiency is measured compared to centrifugals. The roots compressor efficiency calculation incorporates shaft power whereas the centrifugal does not.
- Motor efficiencies for the roots application have exceeded the 100% flow target value but have fallen short of the 25% flow and idle target values.
- Costing has made some improvement towards the target value. It was noticed by the study that most of the product cost resides in the motor and controller. These two products are outside Eaton's control since Eaton purchases these parts.

Expander Plastic Rotor

In Period 1 of this project, straight plastic rotors were successfully tested. In Period 2, helical plastic rotors were designed, built, and tested. Molds were made for both right and left hand rotors. After molding, the rotors were finish coated to reduce rotor-to-rotor and rotor-to-housing clearances. Figure 1 shows the finished rotors and a full plastic expander assembly. The expander was tested without failure to a pressurized or 1.5 bar and rotational speed of 12,000 rpm.

TABLE 2. 2011 to 2015 Goals and Achievements

Flow	Characteristic	Units	Baseline 2011	2015 Project Target		Eaton Test Results	Barriers Objective vs. 2011 Baseline	
				Lower	Upper			
100% (see notes a & b)	Input power with expander	kWe	11.0		8.0	12.1	-27%	10%
	Input power without expander	kWe	17.3		14.0	15.5	-19%	-10.4%
	Combined motor & motor controller efficiency	%	80.0	90.0		95.0	12%	19%
	Compressor efficiency	%	71.0	75.0		57.5	5.6%	-19%
	Expander efficiency	%	73.0	75.0		59.0	9.6%	-19%
25% (see notes c)	Input power with expander	kWe	2.3		1.0	1.6	-57%	-30%
	Input power without expander	kWe	3.3		2.0	1.9	-39%	-42%
	Combined motor & motor controller efficiency	%	57.0	80.0		75.0	40%	32%
	Compressor efficiency	%	62.0	65.0		58.5	4.8%	-5.6%
	Expander efficiency	%	64.0	70.0		44.5	9.4%	-30%
Idle (see notes d)	Input power (1.2 Pressure Ratio) with expander	kWe	600.0		200.0	300.0	-67%	-50%
	Input power (1.2 Pressure Ratio) without expander	kWe	765.0		200.0	300.0	-74%	-61%
	Combined motor / motor controller efficiency	%	35.0	70.0		40.0	100%	14%
	Compressor efficiency	%	61.0	60.0		34.1	-1.6%	-44%
	Expander efficiency	%	59.0	60.0		0.0	1.7%	-100%
n/a (see notes e, f & g)	Turndown ratio (max/min flow rate)	none	20.0	20.0		130.0	0.0%	550%
	Noise at maximum flow dB(A)	dB(A)	n/a		65.0	95.6	n/a	n/a
	Transient time for 10 - 90% of maximum airflow	sec	1.0		1.0	1.0	0.0%	0%
	System volume	liters	15.0		15.0	12.0	0.0%	-20%
	System weight	kg	22.0		15.0	23.5	-32%	6.8%
	System cost	$	960.0		500.0	815.0	-48%	-15%

For a-g flow notes, see Table 1

FIGURE 1. Expander plastic rotors and assembly

Compressor/Expander Validation Testing On Ballard Stack—Baseline Testing

The HD7 system was tested using the existing production air system. The load profile used was a combination of down-polarizations, up-polarizations, constant current operation, and several cycles of the "Whistler Drive Cycle," which is a dynamic load profile taken from field data. The entire baseline test lasted for approximately three days. During testing, a data acquisition system logged process parameters internal to the module. These include stack specific parameters, including voltage and current, as well as air system specific parameters, including flows, temperatures and pressures measured throughout the air system. This test will be the basis for comparison to the Eaton's AMS.

CONCLUSIONS AND FUTURE DIRECTIONS

- End of Period 2 Conclusions
  - Delivered final prototype of the compressor/expander assembly with integrated motor and validation test report
  - Successfully demonstrated twisted plastic rotors in compressor and expander environment
  - Successfully demonstrated that roots compressor value was advanced from baseline
  - Successfully demonstrated that roots compressor + expander value is on par or slightly better than baseline, depending on duty cycle
  - Demonstrated that the use of plastic for most of the components has potential to improve roots expander value for customers
- Beginning of Period 3 Conclusions
  - Delivered two working sets of Eaton's Air Management Systems for Ballard testing
  - Baselined the HD7 system using the existing air system for comparison to Eaton's Air Management System
- Future Directions
  - Complete the performance and validation testing on Ballard's HD7 fuel cell

  - Compressor/expander validation testing On Ballard Stack
  - Durability test as per test plan
- Document Eaton's Air Management System performance capability in test report
- Complete all objectives and milestones by the end of Period 3

FY 2015 PUBLICATIONS/PRESENTATIONS

Presentations

1. Stretch, Dale, "Roots Air Management System with Integrated Expander," 2015 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, June 10, 2015.

2. Stretch, Dale, "Roots Air Management System with Integrated Expander," U.S. DRIVE Technical Meetings, Fuel Cell Tech Team (FCTT), February 11, 2015.