V.H.2 Roots Air Management System with Integrated Expander

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

Project Start Date: July 5, 2012
Project End Date: August 31, 2015

Overall Objectives

Primary Objectives

- 62/64% (base 2011) >65/70% (target 2017) compressor/expander efficiency at 25% of full flow
- 80% (base 2011) >90% (target 2017) combined motor/motor controller efficiency full flow
- 11.0/17.3 kW (base 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 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) 2014 Objectives

- Continue to optimize the peak efficiency island of the compressor and expander to best fit the primary objectives listed above.
- Continue to use computational fluid dynamics (CFD) capability to optimize the compressor and expander inlet, outlet and rotor geometry for peak efficiency.
- Continue to develop plastic expander rotors with required twist angles.
- Finalize the compressor/expander and motor design, create detailed drawing package and procure prototype hardware.
- Develop finalized production cost estimates.
- Conduct performance and validation testing on the complete air system per predefined test plan approved by the DOE.

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 7 air management system hardware capable of meeting the 2017 project targets in Table 1 delivered at project conclusion.

FY 2014 Accomplishments

CFD Modeling

- CFD modeling of the compressors and expanders was perfected. Tool used to better understand the air flow through, and the performance of, various configurations of expanders and compressors.
- A total of 17 expander geometries and configurations were analyzed. The tool has served to identify the correct inlet and exhaust shape and timing to maximize the torque developed by the expander design.
- Two different compressor rotor geometries were analyzed, a three-lobe and a four-lobe. Significant information was gained on the three-lobe rotor compressor analysis. Lessons learned from modeling were incorporated into the final compressor design.

TABLE 1. 2015 and 2017 Project Targets

Characteristic	Units	Current Status	Project Target 2015	DOE Target 2017
Input power[a] at full flowb (with expander/without expander)	kWe	10.6/14.8	8/14	8/14
Combined motor and motor controller efficiency at full flow[b]	%	93	90	90
Compressor/expander efficiency at full flow (compressor/expander only)[b]	%	65/65	75/75	75/80
Input power at 25% flow[c] (with expander/without expander)	kWe	2.0/2.0	1.0/2.0	1.0/2.0
Combined motor and motor controller efficiency at 25% flow[c]	%	82	80	80
Compressor/expander efficiency at 25% flow[c]	%	65/51	65/70	65/70
Input power at idled (with/without expander)	We	405/405	200/200	200/200
Combined motor/motor controller efficiency at idle[d]	%	50	?	70
Compressor/expander efficiency at idle[d]	%	21	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	10.8	15	15
System weight[e]	kg	15.9	15	15
System cost[f]	$	984	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.

Expander Plastic Rotor

- Procured straight rotor injection molding tool and rotor prototypes.
- Tested straight rotors in expander environment.
- Designed helical shape rotors and mold.

Design

- Designed compressor/expander with integrated motor system configuration was packaged with the finalized compressor and expander designs. The air management system built consists of a 260 compressor, a 210 expander, a 12-turn motor and a 30-kW motor controller. System volume and part count have been reduced over the first design iteration.
- Designed and detailed all part drawings for the optimized 260 compressor for hardware fabrication.
- Designed and detailed all part drawings for the optimized 210 expander for hardware fabrication.

Hardware Procurement

- Defined Ballard fuel cell module test specifications, procedures and acceptance criteria.
- Procured the Ballard fuel cell module.
- Ordered and received the 12-turn motors and 30-kw motor controllers.
- Fabricated the 260 compressor and 210 expander hardware per design.

Hardware Testing.

- Tested the 12-turn motor and controller hardware.

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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. The DOE has identified the lack of cost-effective, reliable, and efficient air supply systems 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 to 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 the development of the compressor and expander and finalized the system concept using both experimental and analytical methods.

Compressor Design

The 260 compressor design and fabrication was completed in the last year. The design included the following features:

- Rotors: The rotor set has been optimized for flow performance. High helix angles were used to achieve the higher pressure ratios required by the DOE. The rotors use Eaton's billet aluminum rotor technology to allow for reduced clearances driving up supercharger efficiency.
- Housing: The housing design will feature optimized outlet geometry and an integrated motor adaptor plate. The housing utilizes existing Eaton production seals, bearings, and gears. The timing gears used will be an existing Eaton steel design. Water cooling will be shared with the electric drive motor to increase durability at high pressure ratios.
- Inlet: The inlet has been designed to incorporate the bearing end plate and air inlet with sealed roller bearings into one compact part.

Expander Design

The 210 expander design and fabrication was completed in the last year. The design included the following features:

- Rotors: The rotor set was optimized for minimum leakage. This warranted the implementation of a larger rotor root radius and the use of a higher speed, smaller displacement expander. Two rotor materials will be assessed, a traditional aluminum extrusion construction to minimize complexity and reduce design risk and a new glass-filled plastic rotor over-molded on to a laminated aluminum core as an option to reduce cost and rotating inertia.
- Housing: The latest design incorporates provisions to manufacture the housing in glass reinforced plastic to reduce cost and weight. The housing also features other design improvements such as common shaft, bearing, and seal sizes as well as revised inlet geometry.
- Outlet: The outlet has been designed as a high-temperature plastic part that locates the shaft ends with two incorporated sealed roller bearings with plastic dust covers while maintaining the simplicity of a two-part mold capable part. The rotor outlet timing has been revised to provide for more favorable torque curve, per CFD analysis.
- Gears: The timing gears used will be an existing Eaton plastic/steel hybrid design.

Compressor/Expander with Integrated Motor

The compressor/expander with integrated motor system configuration proposed was achieved through iterative analysis between expander and compressor geometries utilizing actual test data while mathematically correcting for temperature and humidity according to the DOE-specified operating conditions. Effort was placed on effectively matching the expander operating speed to the compressor operating speed at each DOE-specified point. An analytical tool was developed to predict expander power production and operating speed given a known displacement and predicted operating efficiency. This tool compared various expander geometries to tested components in order to find the most appropriate compressor/expander.

Through this process the team concluded that a 260 compressor, a 210 expander, a 12-turn motor supplier motor, and a 30-kW motor supplier controller would be the optimal design that would meet the project technical objectives, Figure 1. This design will contain five shafts and three gears, a modification to the original two shafts and two-gear proposal.

The Phase I air management system performance estimates are listed in Table 1. The parameters listed in this table will be what the final hardware design will be measured against.

System Volume and Part Count

The component and system volumes are within specification and come in at 10.8 liters. The system weight is slightly higher than the targeted 15.0 kg by 0.9 kg but significantly lower than the benchmark weight of 22 kg.

System Design Cost

Eaton worked with Strategic Analysis in generating a preliminary cost for the Eaton air management system. Cost results were estimated at manufacturing rates of 1,000 and 500,000 systems per year. Assembly and manufacturing markup are included in the cost estimate, assuming a 15% markup on all the compressor and expander components and a 10% markup for the motor and motor controller components. The most expensive part of the compressor/expander with integrated motor is the motor controller and motor. The electric motor was considered a purchased component with its cost based on Eaton estimates. The costs for the 500k manufacturing rate are as follows: compressor: $116, expander: $77, motor: $167, motor controller: $360, full assembly and mark-up: $816.

Expander Plastic Rotor

The injection molding tool was completed in September 2013 and first shots occurred in October 2013. Parts filled as predicted in the mold flow analysis with no visual indication of delamination from the aluminum support structure.

Single-rotor testing was conducted at the end of 2013. A single rotor was spun at speeds of 15,000, 17,500 and 20,000 at a constant temperature. Testing was conducted at three temperature set points – 70°C, 90°C and 100°C with dwell times of 5 minutes. The over-molded rotor (Figure 2) was able to achieve the maximum rpm at maximum temperature (20,000 rpm at 110°C) with no evidence of delamination. The next round of testing will include testing to failure to understand material and design capabilities.

CONCLUSIONS AND FUTURE DIRECTIONS

Period 2 Conclusions

- Delivered a design and hardware of the fuel cell air management system (compressor/expander and motor per Figure 1) that is projected to meet the project

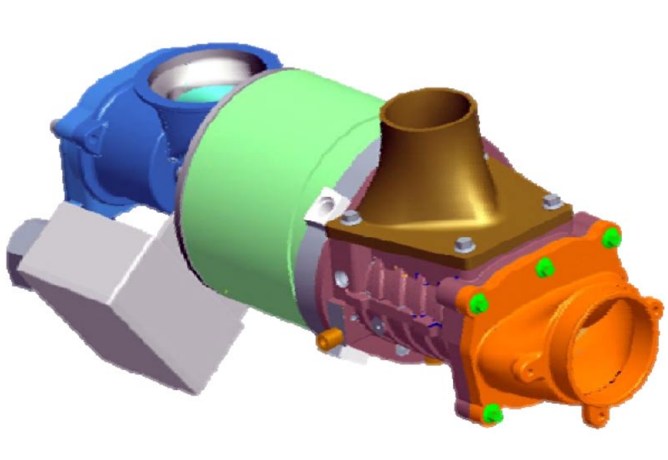

FIGURE 1. Fuel Cell Air System Design

FIGURE 2. As-Molded Rotors

performance targets as stated in the current status section of Table 1.

- Successfully demonstrated straight plastic rotors in compressor environment.
- Successfully demonstrated the capability to use CFD modeling on true dimensional models to predict compressor and expander performance.
- Delivered costing results for complete fuel cell air management system.

Future Directions

- 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 volume including motor, controller, and system enclosure
- Conduct performance and validation testing at Ballard:
  - Write test plan/determine test criteria
  - Integrate design, build, and debug unit on Ballard stack
  - Compressor/expander validation testing on Ballard stack
  - Write test report and review Ballard testing

FY 2014 PUBLICATIONS/PRESENTATIONS

Presentations

1. Stretch, Dale, Roots Air Management System with Integrated Expander, U.S. DRIVE Technical Meetings - Fuel Cell Tech Team (FCTT), April 9, 2014.

2. Stretch, Dale, Roots Air Management System with Integrated Expander, DOE Merit Review - Fuel Cell Tech Team (FCTT), June 18, 2014.