2014 DOE Hydrogen and Fuel Cells Program Review

Project ID: FC103

Roots Air Management System with Integrated Expander

Principal Investigator: Dale Stretch
Eaton Corporation
June 18, 2014

Overview

Timeline

- Project Start Date: 07/05/2012
- Project End Date: 08/31/2015
- % Complete: 60%

Budget Period	Start Date	End Date
1	07/05/2012	08/31/2013
2	09/01/2013	08/31/2014
3	09/01/2014	08/31/2015

Budget

- Total Funding Spent (as of 3/31/14): $1,293,906
- Project Value: $2,627,041
  - DOE Share: $2,101,630
  - Cost Share: $525,411 (20%)
- Funds Obligated: $2,101,630
  - Funding received in FY12: $665,226
  - Funding for FY13: $821,776
  - Funding for FY14: $614,638

Barriers & Technical Targets:

- Air management system drive cycle efficiencies, power & cost
- Cost Target: 2017 = $500
- Input Power at Idle: 2017 = 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	BP1 Progress	DOE Target 2017
Input power[a] at full flow[b] (with expander/without expander)	kW_e	10.6[2]/14.8[2]	8 / 14
Combined motor & motor controller efficiency at full flow[b]	%	93[2]	90
Compressor / expander efficiency at full flow (C/E only)[b]	%	65[5]/65[5]	75 / 80
Input power at 25% flow[c] (with expander/without expander)	kW_e	2.0[2]/2.0[2]	1.0 / 2.0
Combined motor & motor controller efficiency at 25% flow[c]	%	82	80
Compressor / expander efficiency at 25% flow[c]	%	65[5]/51[5]	65 / 70
Input power at idle (1.2 PR)[d] (with / without expander)	W_e	405[2]/405[2]	200 / 200
Combined motor / motor controller efficiency at idle[d]	%	50	70
Compressor / expander efficiency at idle[d]	%	21[5]	60 / 60
Turndown ratio (max/min flow rate)		20	20
Noise at maximum flow	dB(A)	65[1]	65
Transient time for 10 - 90% of maximum airflow	sec	1[1]	1
System volume[e]	liters	10.8[3]	15
System weight[e]	kg	15.9[3]	15
System cost[f]	$	984	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 must be efficient
- Current systems have trouble meeting all these objectives due to:
  - the high cost & complexity of bearings & motor drives used on competing systems
  - the bearing & motor drives systems meeting efficiency & durability requirements 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

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Approach – Budget Period 1-3

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
- ✓ Optimize compressor & expander
- ✓ 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
- ✓ Develop compressor/expander assembly with integrated motor – drive for reduced cost

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 into 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 and Milestone Log

✓

Deliverable 1.0	Project kick-off presentation with revised project management plan	7/17/2012
Deliverable 1.1	Draft Safety Plan	10/04/2012
Deliverable 2.0	Concept design of the compressor/expander assembly with integrated motor	7/3/2013
Year 1 DOE Review	**Conduct a project review with DOE and report on project progress against GO/NO-GO Criteria**	**7/5/2013**
Deliverable 3.0	Final prototype design of the compressor/expander assembly with integrated motor	3/4/2014
Deliverable 4.0	Compressor/expander validation test plan	3/4/2014
Deliverable 5.0	Compressor/expander validation test report **	8/31/2014
Deliverable 6.0	OEM Integration and Test Plan	8/31/2014
Year 2 DOE Review	**Conduct a project review with DOE and report on project progress against GO/NO-GO Criteria**	**8/31/2014**
Deliverable 7.0	OEM validation test report	5/31/2015
Deliverable 8.0	Validated air management hardware	7/31/2015
Deliverable 9.0	System cost and manufacturability study	8/31/2015
Deliverable 10.0	Final Report and Presentation	8/31/2015

→ In progress (Deliverable 5.0)

**Deliverable will include the test results taken on the test matrix developed with ANL and approved by DOE. This test will include dynamic tests, discharge pressures > 3 atm, and full map from idle to 100% flow.

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Accomplishments and Progress
Budget Period 1 - Summary

Task 2.0 Develop Compressor/Expander with Integrated Motor

Subtask 2.1- Optimize compressor

- ✓ Tested various compressor configurations to optimize unit for application
  - ✓ Test Stand: Test cell with relative humidity & inlet temp. control completed
  - ✓ Test Results: 4 compressor configurations have been tested
- ✓ Used CFD modeling to optimize configuration
- ✓ Provided performance data to ANL to validate compressor

Subtask 2.2- Optimize expander

- ✓ Tested various expander configurations to optimize unit for application
  - ✓ Test Results: 4 expander units and 10+ different inlet configurations have been tested
- ✓ Used CFD modeling to optimize configuration
  - ✓ A total of ten (10) expander geometries and configurations analyzed to date
- ✓ Provided performance data to ANL to validate expander

Subtask 2.3- Develop compressor/expander assembly with integrated motor

- ✓ Layout of expander, compressor and motor integrated system
  - ✓ Designed basic package arrangement completed
  - ✓ Low part count & Bearing arrangement
- ✓ Reduced cost plastic component implementation
  - ✓ Design build & test of plastic rotors with integrated aluminum support structure was completed
- ✓ Worked with Strategic Analysis to assess preliminary system design cost data

Accomplishments and Progress
Budget Period 2 - Summary

Task 3.0 Prototype Eaton Compressor/Expander with Integrated Motor

Subtask 3.1- Finalize Detail Drawing Package & Release for Fabrication

- ✓ Compressor Design - 260 compressor CAD model & detail drawings complete
- ✓ Expander Design - 210 expander CAD model & detail drawings complete
- ✓ System Design - Compressor/Expander/Motor configuration completed
  - ✓ Configuration: a 260 compressor, a 210 expander, a 20kW motor & a 30kW motor controller
- ✓ The Ballard Fuel Cell Module Test Specifications, Procedures & Acceptance Criteria have been defined

Subtask 3.2- Procure Prototype Components

- ✓ Compressor Design – released for fabrication
- ✓ Expander Design – released for fabrication
- ✓ 20kw motors ordered
- ✓ 30kw motors controllers ordered
- ✓ PO issued to Ballard for the purchase of the fuel cell
  - ✓ Hardware procurement and test qualifications are targeted for completion by August 2014

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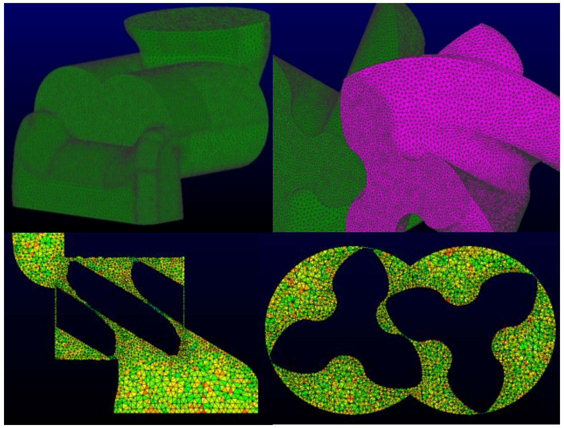
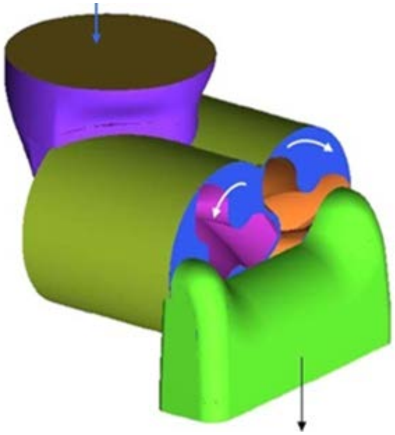
Accomplishments and Progress
CFD Modeling Development (Kettering Progress)

- Eaton has extensive experience with compressor & expander CFD modeling.
  - however a highly refined model (one with tip clearances equivalent to production hardware) is required to accurately determine improvements to compressor and expander efficiency & performance

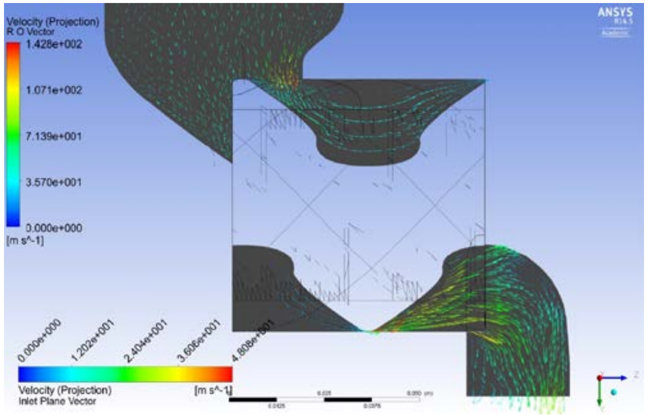
- To obtain correct torque and flow results, accurate rotor tip clearances are required
  - At program start the modelling tip clearance capability was 7 times greater than production clearances
  - Using STAR-CCM+® (improved CFD software), improved modeling of tip clearances by 50%
  - Acquired special software & was able to achieve the targeted production clearances



Mesh of the supercharger-expander



Supercharger meshed geometry



CFD Results

Accomplishments and Progress
Compressor CFD Results (Kettering Progress)

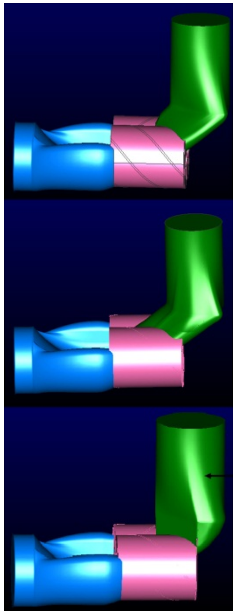
Results

- Larger clearances decrease the overall mass flow rate
- Average torque values are not affected significantly by larger clearances
- Shape of the torque curves appears to depend on the rotor speed & pressure ratio
- At high speed, the torque pulses had a dip in their value at approximately the center of the pulse
- Isentropic efficiency correlation was <12% and <6% for 4 lobe & 3 lobe compressors respectively

Conclusion:

- Torque values are a strong function of the pressure ratio and not significantly dependent on rotor speed
- Torque increases as pressure ratio increases
- Mass flow rate depends on the pressure ratio, rotor speed and clearances

Compressor Outlet Geometries



Seven compressor studies have been analyzed to date:

1. 410 compressor geometry that was correlated to test data
   - CFD correlated to test data to within 10 to 12% on efficiency and mass flow data
2. 410 compressor clearances were investigated, 3 conditions run
3. 260-1 compressor clearances were investigated, 2 conditions run
4. 260-1 compressor outlets configurations were modeled, 3 conditions run
5. 260-2 compressor geometry that was correlated to test data
   - CFD correlated to test data to within <6% on efficiency and mass flow data
6. 260-2 compressor clearances were investigated, 1 condition run
7. 260-2 compressor inlet configurations were modeled, 3 conditions run

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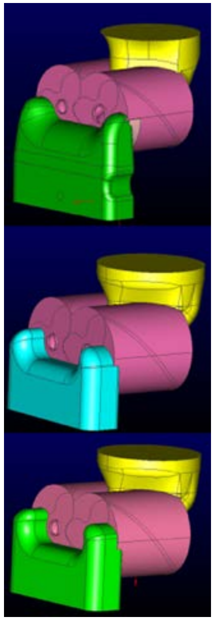
Accomplishments and Progress
Expander CFD Results (Kettering Progress)

Expander Outlet Geometries



Results

- Modeling has shown that the parameters invested to date (given a fixed rotor geometry and speed):
  - have only affected the flow performance & therefore expander efficiency
  - have not affected torque or power performance
- Some geometry modifications, such as diverter and outlet geometries, can improve flow performance
- The item that affects flow performance most is the rotor tip and end clearances

Therefore: to improve the expander flow performance, clearances have to be tightly controlled

Ten expander geometries have been analyzed to date:

1. 250 expander geometry with divider #2
2. 250 expander geometry with Divider #4
   - demonstrated that a correctly designed diverter can improve flow performance. Diverter 2 reduced mass flow but diverter 4 had no effect.
3. 250 expander geometry with an extended inlet
   - had no effect on flow performance at all.
4. 250 expander geometry with bearing clearances added
   - adding the bearing clearance cased mass flow to increase as expected but it did not increase appreciably.
5. 250 expander geometry with ½ tip clearances & no end clearances
   - reducing the rotor tip and end clearances did decrease the mass flow significantly.
6. 210 expander geometry with 1st outlet geometry
7. 210 expander geometry with 2nd Geometry
8. 210 expander geometry with 3rd Geometry
   - had their outlet geometry modified with results showing that it had some effect on flow performance but it was not significant (significant is defined as >2g/s). The 2nd outlet geometry, had the largest flow performance improvement.
9. 210 expander geometry with 2nd Geometry & bearing clearances added
10. 210 expander geometry with 1st Geometry, ½ tip clearances & no end clearances.
    - were similar modification to that of configurations #4 and #5 and the results show similar improvements.

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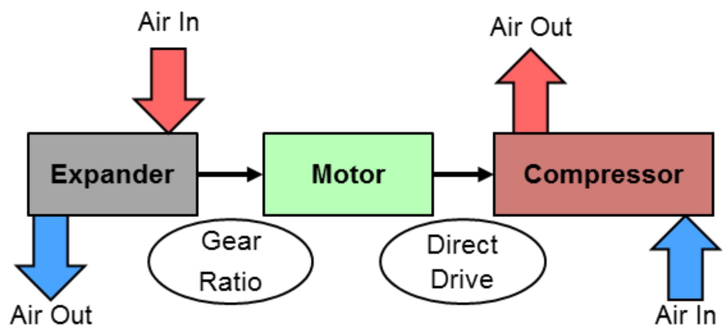
Accomplishments and Progress

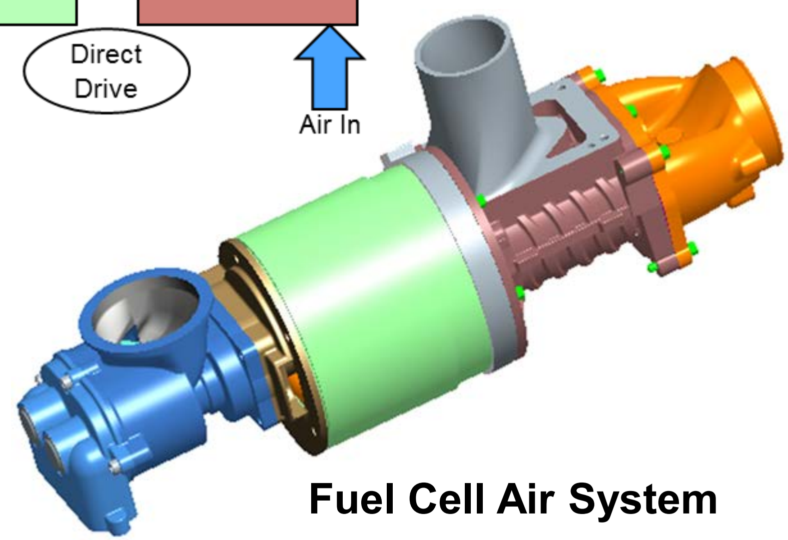
System Design

Latest configuration:

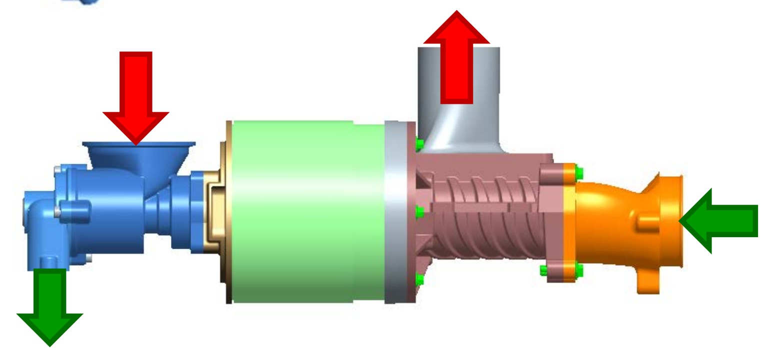
- 260 compressor
- 210 expander
- 20 kW motor
- 30 kW motor controller



- Optimization centered around 100% flow, then 25% flow and finally idle flow
- Motor /Compressor are water cooled
- Motor/Controller peak efficiency 93%
- A gear reduction is located between the motor and expander to optimize expander performance
  - Emphasis was placed on matching the expander to the compressor to improve system performance.



Fuel Cell Air System



Expander Motor Compressor

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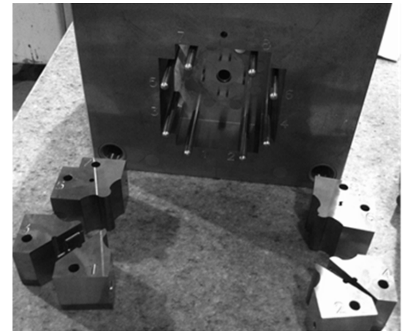
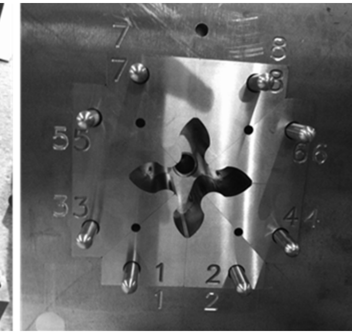
Accomplishments and Progress
Expander Plastic Rotor Analysis

Low Fuel Cell outlet temperatures allow for the use of low cost plastic housings and rotors





Rotor Design

- FEA indicated 4 lobe design has lower stresses in comparison to the 3 lobe design
- High stress from rpm & heat warranted aluminum support structure
- Mold Flow Analysis was conducted to determine gate design for fiber orientation and location

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	[illegible]
2	addition of mechanical locking feature along length of lobe	8000	[illegible]
3	Dovetail interlock along diameter and at the tip of the root	12500	[illegible]
4	Reduced height of aluminum extrusion into the lobe; simplified geometry of dovetail	20,000	[illegible]

Summary of FEA results at 150°C

Rotor Fabrication

- Rotor aluminum support structure
- Injection molding tool

Rotor Testing

- Rotor achieved 20,000 rpm @ 110C with no evidence of delamination

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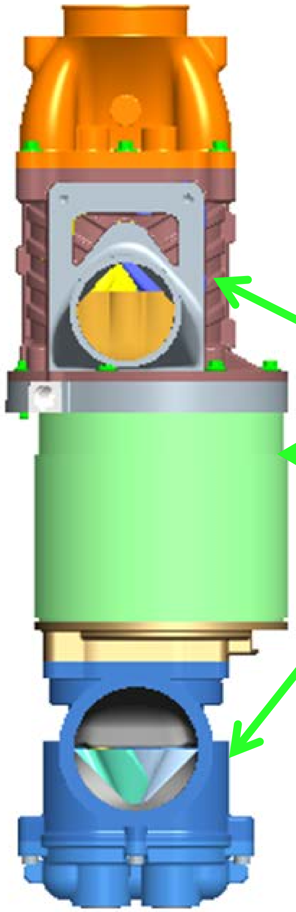
Costing
Eaton Fuel Cell Cathode Air System



Strategic Analysis & Eaton Cost Summary

Eaton 5-shaft 260 Compressor/250 Expander/Motor Unit

Part No.	Component	Qty	Cost
1	Compressor	1	
2	Motor	1	
3	Expander	1	
	Assembly		
	Markup		$479
4	Controller	1	$505
Total			$984

Responses to Last Year Reviewers' Comments

- Use of plastic in expander could potentially have fuel contamination issues.
  - In Eaton/Ballard application, the expander airflow will not be exposed to fuel cell stack, since the expander is after the stack. Therefore plastics used here should not contaminate the stack.
  - In general, Eaton is aware of potential contamination issues that could arise from the use of plastics and will monitor any issues that may arise
  - Team has backup solution that uses aluminum
- It appears Eaton's expander efficiency has dropped from 73% in 2011 to 64% in 2013 & target is much higher @ 75% for 2015. Why did efficiency drop and what is the plan to raise it?
  - The original 2011 numbers are from a centrifugal application
  - Roots expanders currently have a lower efficiency compared to competitive centrifugal expanders
  - Eaton is working on increasing the efficiency, primarily by controlling clearances
- Compressor efficiency is reported at 74% at full flow but the performance maps do not match this high level.
  - The original 74% efficiency value came from an R410 compressor map
  - The plots shown were for an R340 compressor, which had an efficiency of 71%
  - Since the final size was not determined at the time of the publishing, Eaton published the higher of the two numbers
  - Current efficiency number of 65% is for the 260 compressor to be used in final application

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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

Key Remaining Barriers

RISK: Critical speed may be too low with over hug expander rotors.	
LIKELIHOOD: Medium	IMPACT: Rotor contact, System redesign, cost impacts
MITIGATION: Analyze design to drive improvement before parts are made. Using light weight rotor material or support rotors on independent shafts and bearings. This risk mitigated per the requirement to balance the expander size with efficiency which drove the implementation of a step up gear. The gearing eliminated the possibility of dual shaft, over hug design.	
RISK: Material compatibility with exhaust de-ionized water.	
LIKELIHOOD: Medium	IMPACT: Material selection impacted
MITIGATION: Appropriate material selections will be used for all expander parts exposed to the working fluid. Eaton has significant experience with corrosion resistant coating for wetted components in roots blowers used for hydrogen recirculation.	
RISK: Direct coupling of the expander to the compressor may result in FC stack pressure and flow rate control issues.	
LIKELIHOOD: medium	IMPACT: System efficiency reduction and cost impact
MITIGATION: Outlet/bypass valve will be add to maximize control while maintaining effective energy transfer	
RISK: Dry sump gearing will not meet durability requirements	
LIKELIHOOD: Low	IMPACT: premature gear wear resulting in rotor contact
MITIGATION: Appropriate gear design, hardness and coating to prevent premature ware. Contingency will be to go back to wet sump.	

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Proposed Future Work

Period 2 – Items to complete by August 2014

- Prototype Compressor/Expander with Integrated Motor
  - 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 – September 2014 to August 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 required documents have been created & submitted
- All project milestones have been met to date
- Project on track to meet Period 2 Go/No-Go criteria, performance targets & deliverables defined in Period 1
  - Combined motor & motor controller efficiency at full flow[b] = 93%
  - Input power at full flow (with expander/without expander) = 10.6/14.8 kWe
  - Input power at 25% flow[c] (with expander/without expander) = 2.0/2.0 kWe
  - Compressor/expander efficiency at 25% flow = 65/51%

Technical Progress

- CFD Modeling
  - Eaton has made strides in modeling 3 & 4 lobe roots expanders and compressors
  - Tool used to optimize designs
- Expander Plastic Rotor
  - Plastic rotor hardware has been successfully demonstrated through testing
- Develop Compressor/Expander with Integrated Motor
  - Improvements have been made to the expander & compressor design
  - Compressor/Expander matching has been improved upon
  - Design has been completed with detailing in process
- Hardware Procurement
  - The Ballard Fuel Cell Module Test Specifications, Procedures & Acceptance Criteria were defined & PO issued
  - Motor hardware ordered

Summary Table
Progress Towards Project Targets

Table 1.1-1 Project Targets

Characteristic	Units	2011 Status (Centrifugal)	DOE Target 2017	Project Target 2015	Eaton BP1 Progress
Input power[a] at full flow[b] (with expander/without expander)	kW_e	11.0/17.3	8 / 14	8 / 14	10.6[2]/14.8[2]
Combined motor & motor controller efficiency at full flow[b]	%	80	90	90	93[2]
Compressor / expander efficiency at full flow (C/E only)[b]	%	71[4]/73[4]	75 / 80	75 / 75	65[5]/65[5]
Input power at 25% flow[c] (with expander/without expander)	kW_e	2.3/3.3	1.0 / 2.0	1.0 / 2.0	2.0[2]/2.0[2]
Combined motor & motor controller efficiency at 25% flow[c]	%	57	80	80	82
Compressor / expander efficiency at 25% flow[c]	%	62[4]/64[4]	65 / 70	65 / 70	65[5]/51[5]
Input power at idle (1.2 PR)[d] (with / without expander)	W_e	600/765	200 / 200	200 / 200	405[2]/405[2]
Combined motor / motor controller efficiency at idle[d]	%	35	70	70	50
Compressor / expander efficiency at idle[d]	%	61[4]/59[4]	60 / 60	60 / 60	21[5]
Turndown ratio (max/min flow rate)		20	20	20	20
Noise at maximum flow	dB(A)	-	65	65	65[1]
Transient time for 10 - 90% of maximum airflow	sec	1	1	1	1[1]
System volume[e]	liters	15	15	15	10.8[3]
System weight[e]	kg	22	15	15	15.9[3]
System cost[f]	$	960[g]	500	500	984

Data presented at required temperature and humidity

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

2 – Anticipated Performance for System Design as presented

3 – Results generated from CAD drawings

4 – "Adiabatic" Calculation

5 – "Isentropic" Calculation

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