LOW-GWP HVAC SYSTEM WITH ULTRA-SMALL CENTRIFUGAL COMPRESSION

2016 Building Technologies Office Peer Review

Dr. Edward Bennett
e-mail: emb@mechsol.com
Vice President of Fluids Engineering
Mechanical Solutions, Inc.
Project Summary

Timeline:
Start date: 10/2015
Planned end date: 6/2017

Key Milestones
1. Milestone 3.3.1; 1/29/16
2. Milestone 2.1.1 ~40% complete; 1/29/16

Budget:
Total Project $ to Date:
- DOE: $134,406 + $56,776 (fy: 2016)
- Cost Share: $52,867

Total Project $:
- DOE: $999,921 ($362,794 Approved Budget)
- Cost Share: $251,525 ($125,886 Approved Budget)

Key Partners:
- Lennox International, Inc.
- TURBOCAM International, Inc.

Project Outcome:
Advance unrealized design potential of small centrifugal vapor compression in conjunction with advanced heat exchanger design to reduce environmental burdens with the use of low-GWP refrigerants while cost-effectively maintaining performance.
Purpose and Objectives

Problem Statement: Advance unrealized design potential of small centrifugal vapor compression in conjunction with advanced heat exchanger design to reduce environmental burdens with the use of low-GWP refrigerants while cost-effectively maintaining performance.

Target Market and Audience: This project is targeted toward residential and commercial air conditioning. The market is approximately 3 quads of cooling for both residential and commercial. The audience is new units selected for low-GWP refrigerant capability.

Impact of Project:

• **Project Output** – Technical performance goals met, technical and manufacturing pathway established, and prototype for efficient use of low-GWP refrigerants in HVAC applications

• **Near-term outcomes**: Private sector aware of technology through investment/collaboration, begin additional investment to refine technology/reduce cost

• **Intermediate outcomes**: Continued partnership with private sector system and component manufacturers to refine technology and reduce cost, introduce to market

• **Long-term outcomes**: Enable cost effective and energy efficient shift to low-GWP refrigerants in HVAC industry
Approach: Develop conceptual model in collaboration with system vendor to determine efficiencies, system design and manufactured cost. Refine design and build/test prototype to validate solution.

Key Issues:

1. **Efficiency** – Low-GWP refrigerants are new and untested in this application. Early compressor studies are based on isentropic efficiency, but system efficiency results required.

2. **System integration** – Small centrifugal is a departure from current HVAC applications in this size range. Need good integration into system, including operating methodology, materials compatibility, etc. Heat exchanger is an integral component.

3. **Cost** – Technology will need to be cost effective to be adopted by industry and subsequently consumers.

Distinctive Characteristics: Determine system efficiency and cost estimates early in program.
Progress and Accomplishments

Accomplishments:
- Study of various low-GWP refrigerants performed and downselected
- Conceptual aero design completed
- Preliminary heat exchanger design completed, parts being sourced
- Conceptual bearing and motor design completed

Market Impact:
- Presenting findings to date at Purdue Compressor Conference Aug 2016
- Still early in project (Budget Period 1)

Awards/Recognition:
- None to date

Lessons Learned:
- Business Development negotiations with partners can be very time consuming
Project Objectives

- Design and development of an ultra-small, efficient, maintenance-free, oil-free, inexpensive centrifugal compressor, including aero components, rotor-bearing system, inverter and motor for a 5-ton air conditioning system
- Optimization for partial load efficiency, without sacrificing peak load performance
- Design for manufacturability and cost
- Validation and system integration of a high effectiveness heat transfer system, engineered for a very low-GWP refrigerant, e.g., microchannel heat exchanger
- Analysis of:
  - very low-GWP refrigerant compatibility with system materials
  - throughput benefits of centrifugal compression of lower density, very low-GWP’s
- Quantification of beneficial lifecycle impacts of centrifugal technology, including installation, diagnosing, and servicing of systems
- Optimization for unitary “drop in” replacement, including flammability and safety risks, suction line pressure drop, and performance relative to outdoor temperature
- Testing of prototype system
Design and Prototype Development Flowchart

- **System Design**
- **Preliminary Compressor Aero Design**
- **Detailed Compressor Aero Design**
- **Detailed Compressor Manufacturing and Mechanical Design**
- **Oil Free Bearing and Motor Design**
- **Prototype Development and Testing**
- **Integration with Lennox Air Conditioner**
System Design

• Conducted by Lennox
  • System design consisting of all components (Compressor, heat exchanger, etc.), using Cycle_D code

• Multiple refrigerants examined
  • Several HFO blends were evaluated
Preliminary Aero Design

• Conducted using PCA Vista Design Code and CFturbo
• Both codes employed modified Redlich Kwong and Peng Robinson Equation of State (EOS) to simulate Refrigerant PVT behavior
Detailed Aero Design

• Upon Completion of the preliminary design, a detailed 3-dimensional geometry of the centrifugal compressor was made using specific turbomachinery design software (ANSYS and CFturbo).
• The flowpath was analyzed using the real gas CFD code, STAR-CCM+.
• A secondary flowpath was added to the system using the NX and Pro-Engineer CAD products to add fidelity to the analyses.
• Complete analyses were conducted for subject refrigerants.
• The analyses were completed at the rated condition, as well as a appropriate turndown condition to ensure proper off-design performance.
• The effect of the foil bearings were considered in these analyses. A supply flow was taken from the impeller. This flow will feed the bearings, and provide motor cooling flow.
Compressor Coupled CFD Analysis
Project Integration and Collaboration

Project Integration:
MSI and Lennox are coordinating system design parameters to guide development. Lennox participates in requirements definition, design reviews, and parallel development.

Partners, Subcontractors, and Collaborators:
Project partner – Lennox International, Inc.

Communications:
Presenting findings to date at Purdue Compressor Conference Aug 2016
### Project Plan and Schedule

#### Major Task Schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>SOPQ Task #</th>
<th>Task or Milestone/Deliverable Description</th>
<th>Performer (if different from recipient)</th>
<th>Task Completion Date</th>
<th>Original Planned</th>
<th>Revised Planned</th>
<th>Actual</th>
<th>% Complete</th>
<th>Progress Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Program Management - Ongoing</td>
<td>Principal Engineer I</td>
<td>9/30/2017</td>
<td>10/12/2017</td>
<td>20%</td>
<td></td>
<td></td>
<td>Project Schedule has been shifted by 2 months due to late kickoff meeting</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Requirements Definition</td>
<td>Vice President</td>
<td>6/31/17</td>
<td></td>
<td>60%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>First version of Requirements Document complete</td>
<td>Vice President</td>
<td>1/29/2016</td>
<td>2/28/2016</td>
<td>40%</td>
<td></td>
<td></td>
<td>First Version Of Requirements Document To Be Finalized At Concept Design Review</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>Materials Compatibility Investigation</td>
<td>Lennox</td>
<td>4/30/2016</td>
<td></td>
<td>70%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>Preliminary materials selection complete</td>
<td>Lennox</td>
<td>1/29/2016</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td>Refrigerant Selected</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>Final materials selection</td>
<td>Lennox</td>
<td>7/30/2016</td>
<td></td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Market Transformation</td>
<td></td>
<td>6/30/2016</td>
<td></td>
<td>10%</td>
<td></td>
<td></td>
<td>Subtask 4.2 (identified TURBOCAM) Conducting In Concert With Production Cost Estimate Effort</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Obtain letter of interest from potential manufacturing partners</td>
<td></td>
<td>4/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>Conceptual Design</td>
<td>Vice President</td>
<td>2/28/2016</td>
<td></td>
<td>60%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>Aerodynamic Design</td>
<td></td>
<td>1/15/2016</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td>Per DOE/MSI Aerodynamic Design Review (1/19/2016)</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>Motor Type Selected</td>
<td></td>
<td>3/1/2016</td>
<td></td>
<td>5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>Economical bearing solution identified</td>
<td></td>
<td>2/28/2016</td>
<td></td>
<td>10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>Preliminary &amp; Critical Design</td>
<td>Vice President</td>
<td>8/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>Final integrated compressor/motor design efficiency meets 78%</td>
<td></td>
<td>8/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>Refrigerant selection complete</td>
<td></td>
<td>8/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>Go/No-Go Decision Point (Continuation Report)</td>
<td></td>
<td>6/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>Prototype Procurement and Assembly</td>
<td>Principal Engineer I</td>
<td>3/31/2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>LCCP improvement of at least 38% over typical A/C unit</td>
<td></td>
<td>9/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>Checkout test successful</td>
<td></td>
<td>3/31/2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>Heat Exchanger Design</td>
<td>Lennox</td>
<td>12/31/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>Heat exchanger types for evaluation selected</td>
<td>Lennox</td>
<td>11/30/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>Achieve condenser HX cost parity vs. baseline R-410A condenser</td>
<td>Lennox</td>
<td>12/31/2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>Procure Heat Exchanger Prototype</td>
<td>Lennox</td>
<td>1/30/2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>Integrated compressor/motor and a/c system tests</td>
<td>Principal Engineer I</td>
<td>4/30/2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>100% speed test for compressor</td>
<td>Principal Engineer I</td>
<td>4/30/2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>Final Design</td>
<td>Vice President</td>
<td>6/31/17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>Final manufactured component cost still below $275 per unit (Go/No-Go Meeting)</td>
<td></td>
<td>6/31/17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Project Dates:
- **Start:** 10/2015
- **End:** 6/2017

### Current and Future Work
- See Schedule
Project Budget:

- **DOE**: $999,921 ($362,794 Approved Budget)
- **Cost Share**: $251,525 ($125,886 Approved Budget) - Lennox International, Inc

Variances:
- Currently no variances specific to project

Cost to Date:
- **DOE**: $134,406 (CY 2015) + $56,776 (Q1 CY 2016 – End Of Q1 CY 2016)
- **Cost Share**: $52,867 (CY 2015)

Additional Funding:
- Strategic Partner (Lennox International, Inc.) To Dedicate $251K Cost Share

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOE</strong></td>
<td>$134,406</td>
<td>$240,375</td>
<td>$625,140</td>
</tr>
<tr>
<td><strong>Cost-share</strong></td>
<td>$52,867</td>
<td>$71,517</td>
<td>$127,141</td>
</tr>
</tbody>
</table>
Next Steps and Future Plans:

- Consider 2-stage compressor
  - Longer lifecycle
  - More refrigerant options
  - Applicable to heat pumps, including cold climate
- Need to investigate higher resolution 3-d printing for various materials