Heat Pump Clothes Dryer
2017 Building Technologies Office Peer Review
Project Summary

Timeline:
Start date: Oct 1, 2012
Planned end date: Sept 30, 2017

Key Milestones
1. Experimental validation to demonstrate utility of model as design tool. Met: Jan 31, 2017

Key Partners:
GE Appliances (CRADA)

Budget:
Total Project $ to Date:
• DOE: $3770k

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• DOE: $3770k

Project Outcome:
Evaluate the technical and commercial viability of a residential heat pump clothes dryer, configured for US market, that enables reduced energy consumption meeting 2020 MYPP target of EF greater than 6.
Purpose and Objectives

Problem Statement: Evaluate the technical and commercial viability of a residential heat pump clothes dryer with energy factor > 6 lb/kWh. Dozens of models are available in Europe, but very few in the US. Research is needed to configure a HPCD to meet U.S. consumer desire for drying large loads with fast dry times and low price premium.


Impact of Project: Introducing a high energy factor HPCD with high energy factor, fast dry time, and modest price premium is needed to finally create a substantial market for heat pump dryers in the U.S.
Objective

• Advance drying state-of-the-art at unprecedentedly low cost

Combined energy factor: \( CEF = \frac{\text{cloth mass dried}}{\text{electricity consumed}} \)

- **Project goal**: Fast, E-STAR
- **Measured 2\textsuperscript{nd} generation ORNL/GEA prototype**
- **State of art HPCD**
- **Existing HP products (LG, WP, Asko)**
- **Existing electric resistance products**

Graph:
- **Dry time [minutes]**
- **CEF [lb\text{cloth}/kWh]**
- **DOE 8.45 lb load**
**Approach**

**Tactic:** New, more rigorous approach to modeling and validation to minimize component sizes and costs while maintaining favorable dry time and efficiency.

**Key Issues:** Dry time, price premium, and efficiency. A successful product in the US market would need to address all three of these issues:

- Efficiency needed to differentiate product in the market
- Dry time needs to be acceptable to consumers
- Price premium needs to be typical for premium laundry products

**Distinctive Characteristics:** Faster dry time, lower projected cost, and higher CEF compared with existing HPCDs on the US market.
Heat Pump Clothes Dryer Cycle

- “Closed” cycle – ductless, no hole through wall
- Recover condenser waste heat to evaporate water in clothes
- Use evaporator to condense and remove moisture
HPCD Modeling: a Highly Coupled System

- Despite apparent simplicity in a process diagram, HPCD is a complex and highly-coupled system.
- It is only loosely coupled to any fixed state points.

- Approach: fresh modeling framework and validation by prototyping.
Notes:
• Dry time and compressor discharge temperature - important design targets.
• Clothing moisture content mass ratio ($\frac{\text{lb}_{\text{water}}}{\text{lb}_{\text{cloth}}}$) starts at 57.5%, ends at 4%.
Progress and Accomplishments

Accomplishments:
• Accurate hardware-based design model developed in ORNL’s HPDM platform
  – New drum effectiveness approach advances the science of dryer analysis
• 2 generations of prototypes fabricated and evaluated
• Cost reductions achieved via model-guided design process

Market Impact:
• Over 50% reduction in incremental manufacturing cost achieved
• Assessment of commercialization potential under consideration

Awards/Recognition: None

Lessons Learned: Key parts of modeling effort can be simplified; other key parts cannot. Some simplified models are being disseminated in publications.
Progress and Accomplishments: Timeline

FY12-13
Combined washer/dryer research

Gen 1 Prototype
- Gen 1 Prototype fabrication
- Establish CRADA
- Gen 1 Delivered to ORNL
- Charge optimization; evaluation
- Establish dryer modeling capability
- Develop drum effectiveness model

Characterize various drums for their effectiveness as function of key variables
Incorporate leakage into modeling framework

FY14
FY15
FY16

Gen 2a Prototype
- Gen 2 Prototype design
- Gen 2 Prototype fabrication
- Initial evaluation
- Sealing improvements
- EXV changed
- Charge optimization

Gen 2b
- Gen 2b design
- Gen 2b fab. and evaluation
- today

FY17
Accomplishments: Validated Design Model

- Model predictions accurate compared with 12-test experimental test matrix:

<table>
<thead>
<tr>
<th>Test #</th>
<th>Deviation: CEF [-]</th>
<th>Deviation: dry time [min]</th>
<th>Deviation: compressor discharge [°F]</th>
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<tbody>
<tr>
<td>1</td>
<td>-4.0%</td>
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<td>2</td>
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<td>-0.7</td>
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<td>12</td>
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<td>0.7</td>
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<tr>
<td>Average</td>
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<tr>
<td>Stdev</td>
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<td>Max dev</td>
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<td>21.3</td>
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Progress and Accomplishments

System incremental manufacturing cost lowered by more than 2x, compared with conventional heat pump dryers.

Enabled by:

– Rigorous modeling and validation framework
– Consideration of system-level effects of component selections
– New method of drum heat and mass transfer effectiveness modeling
– Pursuing cost-effective design changes suggested by model

Gen 2a prototype under evaluation at ORNL
Mathematical Model:

\[ \omega_{out,i} = \omega_{s,i} - (\omega_{s,i} - \omega_{in,i}) \times (1.0 - E_M) \]

\[ T_{out,i} = T_{s,i} - (T_{s,i} - T_{in,i}) \times (1.0 - E_H) \]

\[ Q_i = m_{air,circ} \times (H_{out,i}-H_{in,i}) \]

\[ WaterFlow_i = m_{air,circ} \times (\omega_{out,i} - \omega_{in,i}) \]

• Definition newly applied to dryer application
• Effectiveness has strong dependence on RMC
• Advanced the science of clothes dryer analysis: first publication of empirical drum effectiveness-based HPCD modeling and design
Developed New Leakage Characterization Technique

• Seal everything *not* to be measured
• Pressurize drum with calibrated blower to determine flow coefficient (Cv) of segment under test. Repeat for all segments.
• Measure pressures in situ during normal operation
• Combine Cv and ΔP measurements to calculate leakage flows

\[ \text{Volume flow} = Cv \sqrt{\Delta P} \]
Model Accurately Predicts Performance; State Points

- Predicted energy factor within 10%
- Predicted drying cycle time within 5 minutes
- Predicted max discharge temperature within 20°F
Project Integration and Collaboration

**Project Integration**: Commercialization prospects under consideration by industry partner

**Partners, Subcontractors, and Collaborators**: Undergraduate interns: Dakota Goodman, University of Louisville; Amar Mohabir, University of Florida

**Communications**:
Next Steps and Future Plans

- Finalize Gen 2b design refinements – final generation of prototype incorporating lessons learned
- Finalize experimental evaluation
- Commercialization determination
REFERENCE SLIDES
Project Budget

Project Budget: 3770k
Variances: None
Cost to Date: 3613k
Additional Funding: None

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<th>FY 2012 – FY 2016 (past)</th>
<th>FY 2017 (current)</th>
<th>FY 2018 (planned)</th>
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* In-kind contribution from CRADA partner – exact total is confidential information
# Project Plan and Schedule

## Project Schedule

**Project Start:** Oct 1, 2012  
**Projected End:** Sept 30, 2017

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<th>Task</th>
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<th>FY2017</th>
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<td>Q4 (Jul-Sep)</td>
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**Past Work**

- Develop air leakage model
- Fabricated 2nd generation prototype
- CEF evaluation
- GO/NO-GO: Design goals met
- GO/NO-GO: Model validated

**Current/Future Work**

- Next generation design
- Evaluate CEF