Heat Pump Clothes Dryer

2017 Building Technologies Office Peer Review

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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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
2. Document next generation design. Upcoming: Apr 30, 2017

Key Partners:

GE Appliances (CRADA)

Budget:

Total Project $ to Date:

- DOE: $3770k

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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.

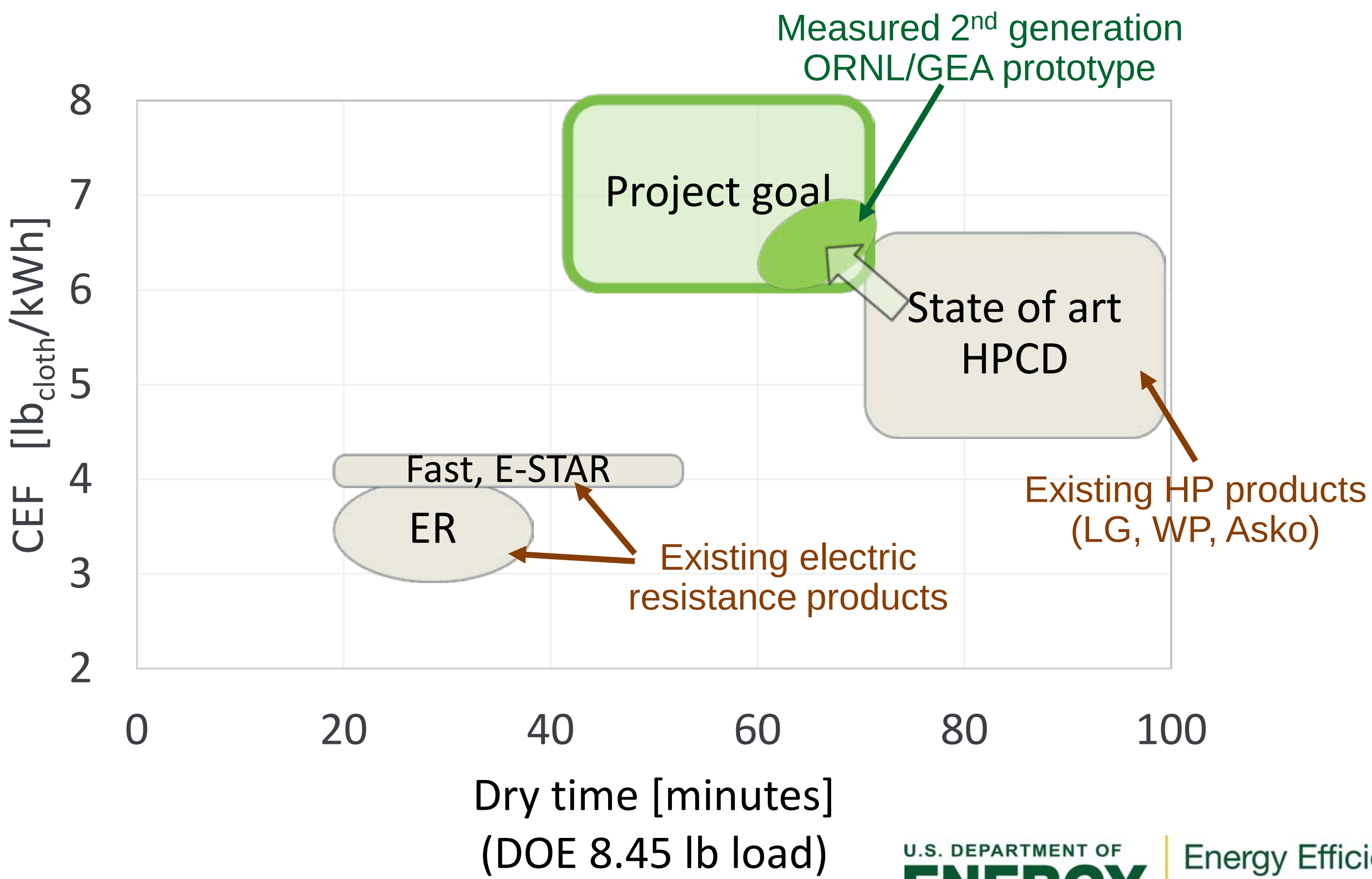
Target Market and Audience: Residential clothes drying. Unit shipments of 8M units/year, at $300-1500 retail price (weighted towards $600-1000 range). Market size (2017) ***622 TBtu/yr***.

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: $$CEF = \frac{cloth\ mass\ dried}{electricity\ consumed}$$



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Approach

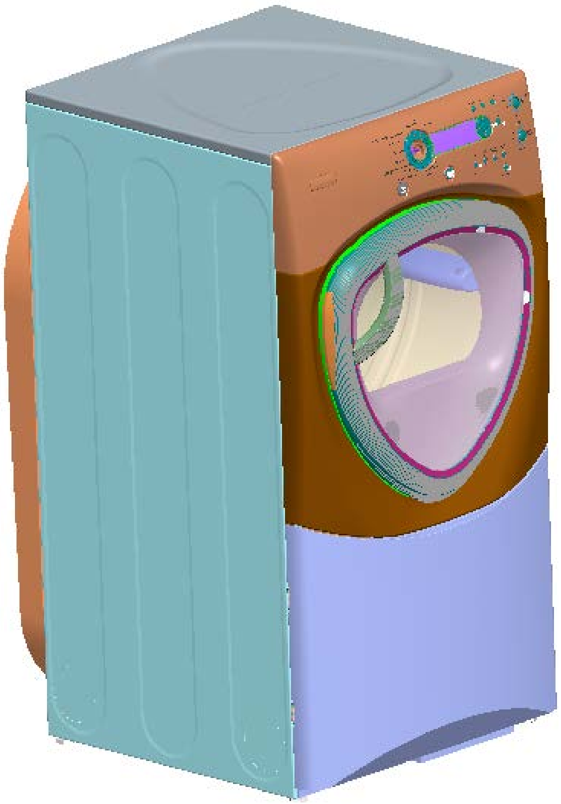
Tactic: New, more rigorous approach to modeling and validation to minimize component sizes and costs while maintaining favorable dry time and efficiency.

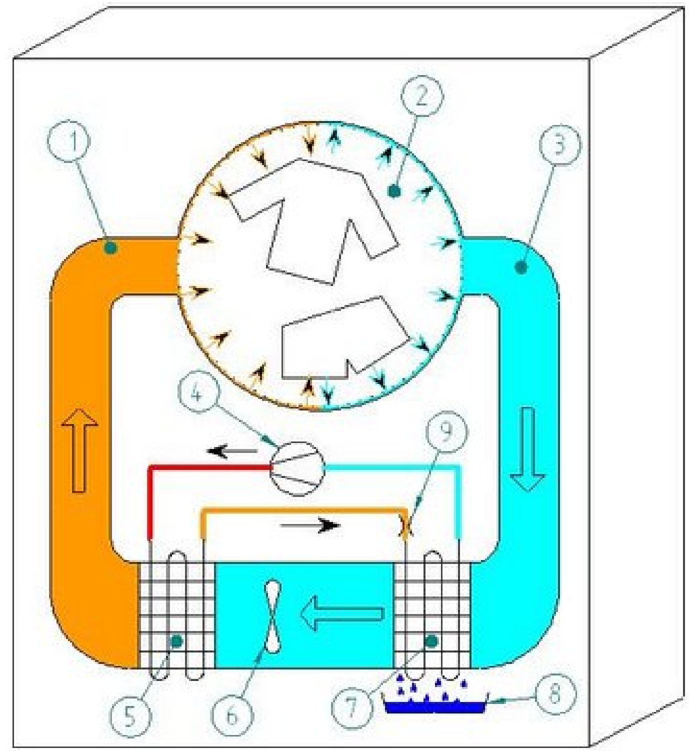
Key Issues: Dry time, price premium, and efficiency. A successful product in the US market would need to address all three of these issues:

- 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



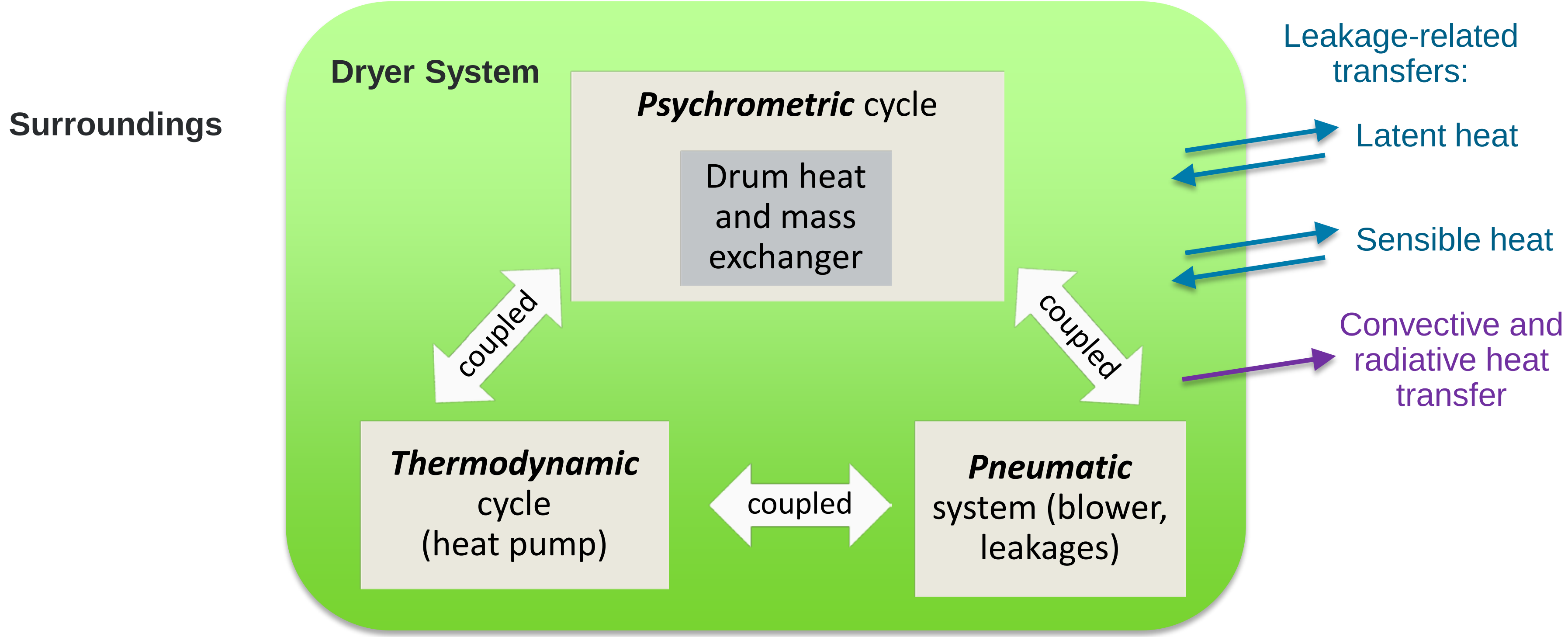


1. Hot dry air
2. Drum
3. Cold wet air
4. Compressor
5. Condensor or gas cooler
6. Circulation fan
7. Evaporator
8. Condensate
9. Expansion valve

- “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

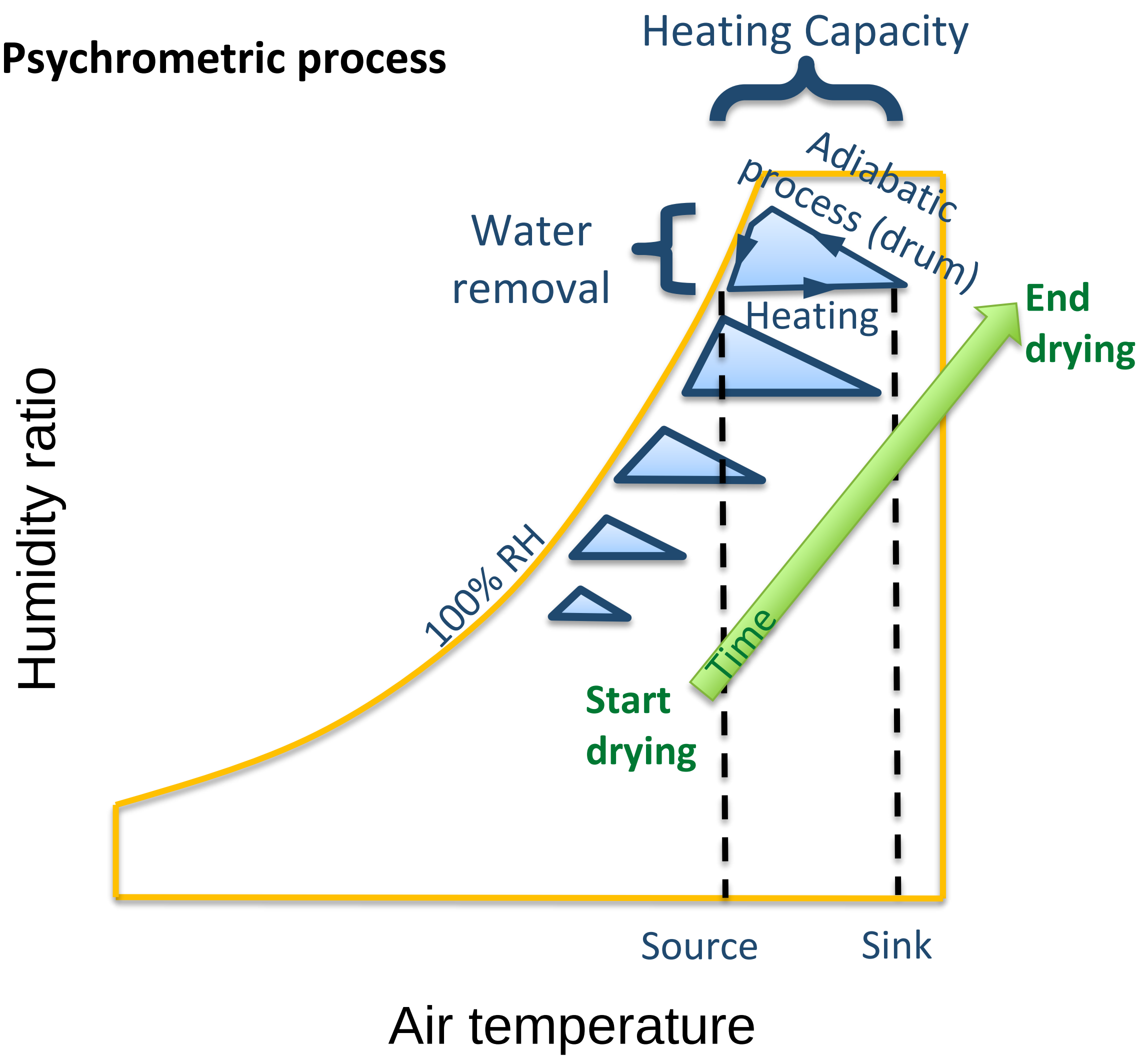
- Despite apparent simplicity in a process diagram, HPCD is a complex and highly-coupled system.
- It is only loosely coupled to any fixed state points.



- Approach: fresh modeling framework and validation by prototyping

HPCD Modeling: a Transient Drying Process

Psychrometric process



Notes:

- Dry time and compressor discharge temperature - important design targets.
- Clothing moisture content mass ratio (lb_{water}/lb_{cloth}) starts at 57.5%, ends at 4%.

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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

Experimental activities | Modeling activities | Other activities

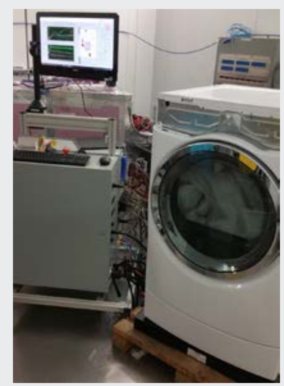
FY12-13 Combined washer/ dryer research

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

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

FY12-13 | FY14 | FY15 | FY16 | FY17 | today

Accomplishments: Validated Design Model

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

Test #	Deviation: CEF [-]	Deviation: dry time [min]	Deviation: compressor discharge [°F]
1	-4.0%	-0.1	7.8
2	-2.5%	-0.7	2.7
3	-3.9%	1.1	19.4
4	-5.2%	2.1	17.7
5	9.2%	-4.5	1.5
6	10.0%	-5.3	0.4
7	6.9%	-1.6	13.6
8	2.5%	-1.8	21.3
9	1.1%	-1.1	7.2
10	3.6%	-4.5	5.9
11	-0.9%	-0.4	20.5
12	0.3%	0.7	15.3
Average	1.4%	-1.3	11.1
Stdev	4.9%	2.2	7.4
Max dev	10.0%	5.3	21.3

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

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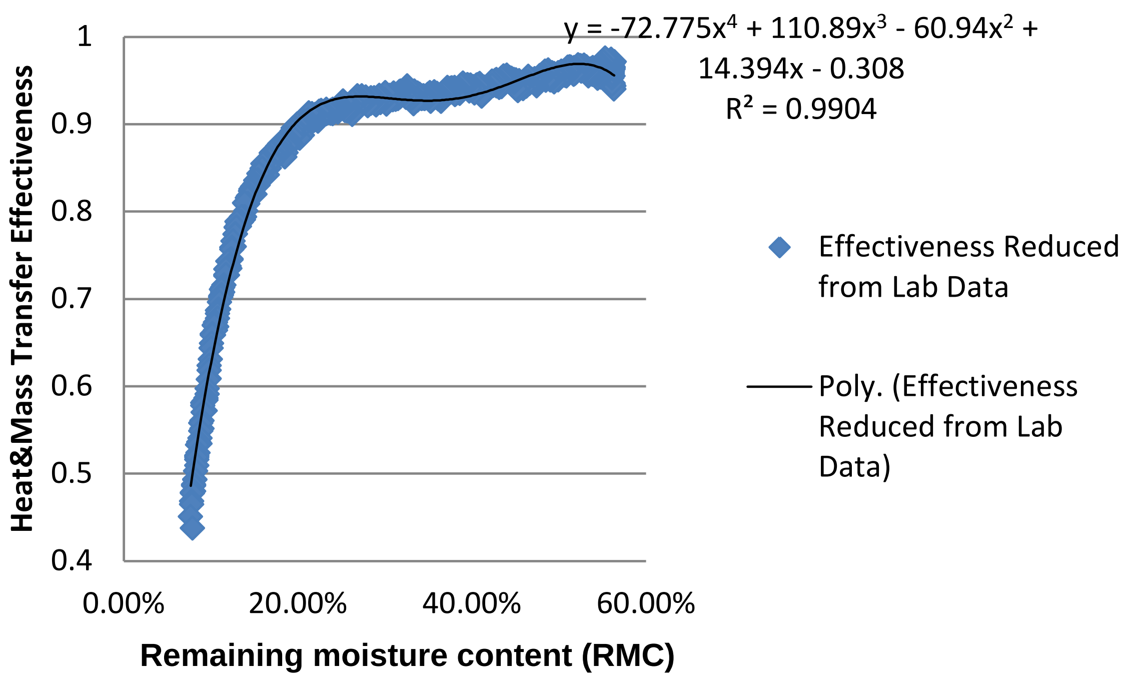
Empirical Drum Heat & Mass Transfer Effectiveness



- 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

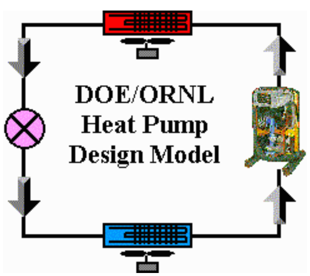
Mathematical Model:

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

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

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

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



Model VCS in the transient process

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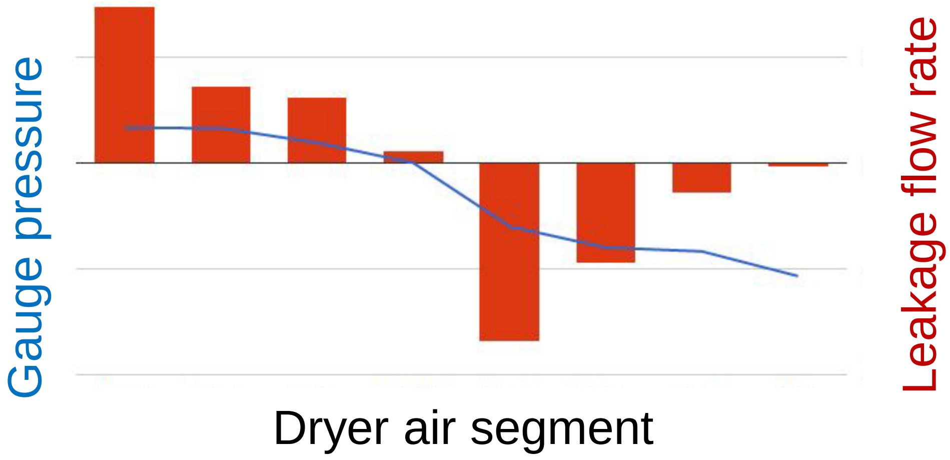
Developed New Leakage Characterization Technique

- 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

$$\boldsymbol{Volume\ flow = Cv\sqrt{\Delta P}}$$



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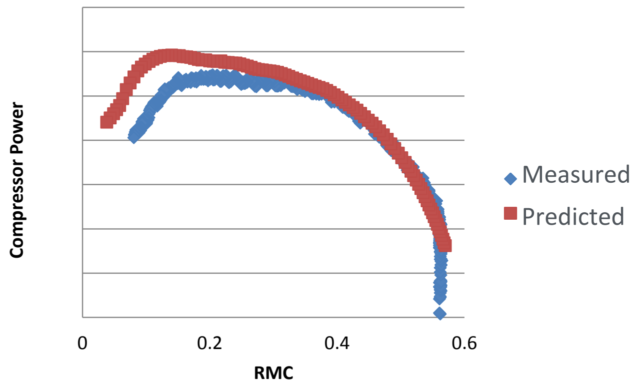
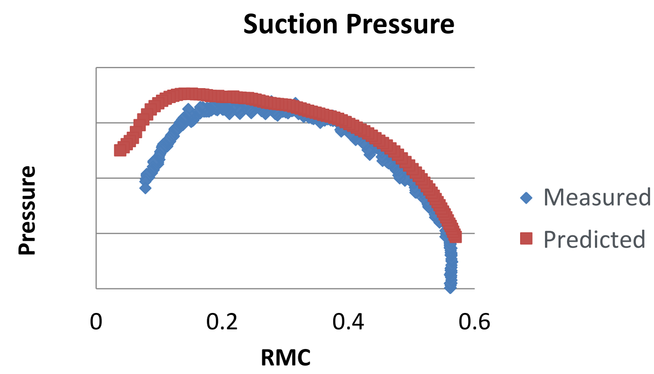
Model Accurately Predicts Performance; State Points

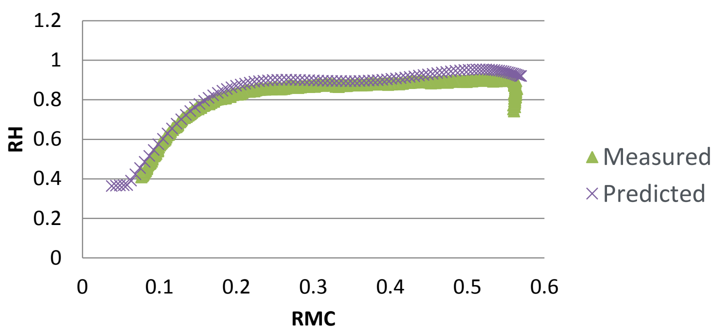
Power consumption

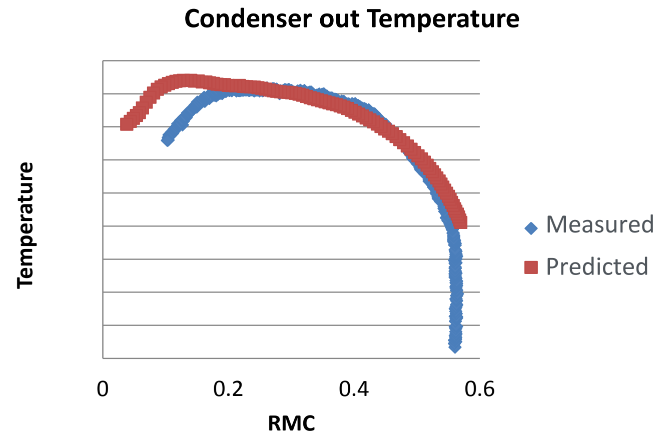


Refrigerant state points



Air side: evaporator inlet RH





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

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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:

- Shen, B., Gluesenkamp, K., Bansal, P., Beers, D. (2016). "Heat pump clothes dryer model development". *16th Refrigeration and Air Conditioning Conference*, Purdue University, West Lafayette, IN, 7/2016.
- Gluesenkamp, K.R., Goodman, D., Shen, B., Patel, V. "An Efficient Correlation for Heat and Mass Transfer Effectiveness in Tumble-type Clothes Dryer Drums" (manuscript in preparation)
- Pradeep Bansal, Amar Mohabir, William Miller (2016). "A novel method to determine air leakage in heat pump clothes dryers". *Energy* 96:1-7.

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

Budget History					
FY 2012 – FY 2016 (past)		FY 2017 (current)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
3392k	*	378k	*	0	0

* In-kind contribution from CRADA partner – exact total is confidential information

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Project Plan and Schedule

Project Schedule		
Project Start: Oct 1, 2012		Completed Work
Projected End: Sept 30, 2017		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned)
		Milestone/Deliverable (Actual)
		Go/No-Go Milestone

	FY2015				FY2016				FY2017			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
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												

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