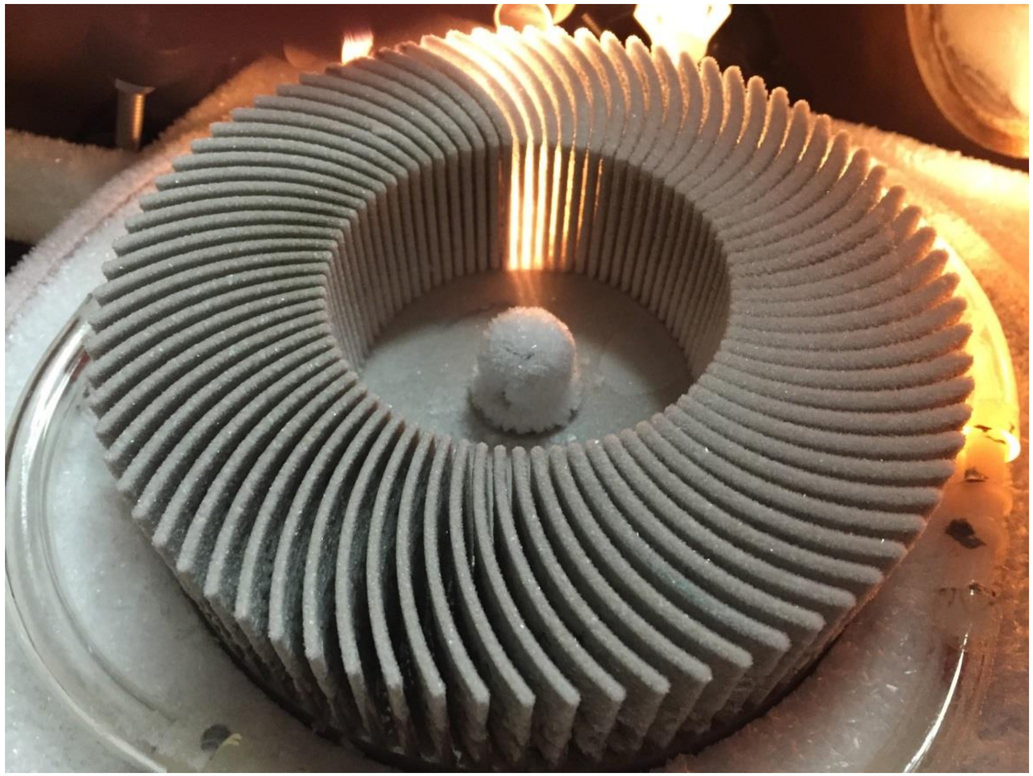
High-Performance Refrigerator Using Novel Rotating Heat Exchanger

2016 Building Technologies Office Peer Review



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Omar Abdelaziz, abdelazizoa@ornl.gov
Oak Ridge National Laboratory

Project Summary

Timeline:

Start date: 10/01/2014

Planned end date: 09/30/2016

Key Milestones

1. Development of the first prototype
2. Successful one-week-long open circuit testing
3. The rotating HX and frost collector unit successfully run and tested for one week

Budget:

Total Project $ to Date:

- DOE: $895,977
  - ORNL: $475,477
  - SNL: $245,000
  - UMD: 175,500
- Cost Share: $99,500

Total Project $:

- DOE: $895,977
- Cost Share: $99,500

Key Partners:

Sandia National Laboratories
University of Maryland

Project Outcome:

Run the first generation prototype for 1 week uninterrupted

Developed market assessment study

Developed frost collector model

Purpose and Objectives

Problem Statement: Develop cost effective higher efficiency residential refrigerators – targeting 12% efficiency improvement with a simple payback of less than 3 years.

Target Market and Audience: the target market is residential refrigerators. The 2030 total residential refrigeration energy consumption amounts to 0.99 Quad.

Impact of Project:

- This project will result in the development of the first HVAC&R application of a novel heat exchanger concept – air bearing heat exchanger or rotating heat exchanger (RHX) which has the potential to significantly improve the performance, reduce the frost penalty and the accompanying frequent defrosts.
- According to our market assessment study market share of the total market at ultimate adoption (>10 years following commercial viability) could

Scenario	Market Share (# units)	Maximum 10-Year Savings ($M)	Maximum 10-Year Job Creation
1.5 Year Payback	48% (5 million units)	$590 – 910	4,340 – 6,700
5.0 Year Payback	8% (> 1 million units)	$90 – 330	660 – 2,450

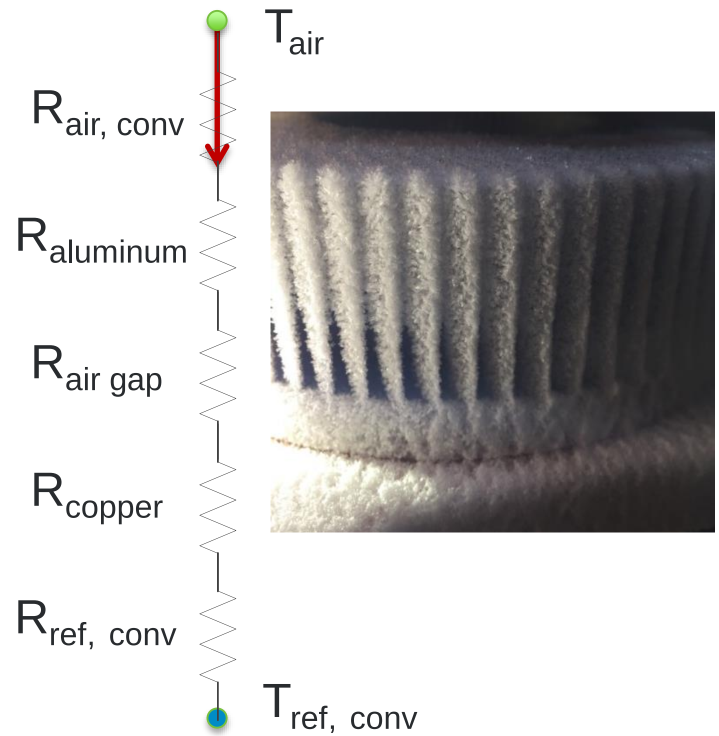
Approach

Approach:

Develop next generation refrigerator evaporators based using the RHX technology

Key Issues:

- Frost formation and release from a rotating surface
- Performance impact on the refrigerator
- Long term reliability
- Cost



Distinctive Characteristics:

Air-Bearing heat exchanger technology provide potential for performance improvement. This is the first attempt at applying it in a realistic HVAC&R product to boost its efficiency.

- Major characteristics: quiet, frost resistant, compact

Progress and Accomplishments

Accomplishments:
- Evaluated the performance of RHX under varying operating conditions
- Successfully run the RHX in a benchtop refrigerator for 7 days – uninterrupted
- Performed Market assessment

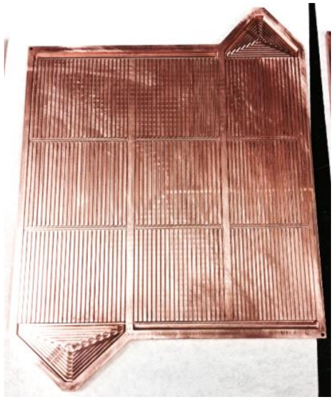
Market Impact:
- Identified frost deterrence capabilities of RHX
- Evaluated energy benefit of RHX
- Identified potential for market share growth (up to 48% at ultimate adoption) and indirect job creation (up to 6,700)

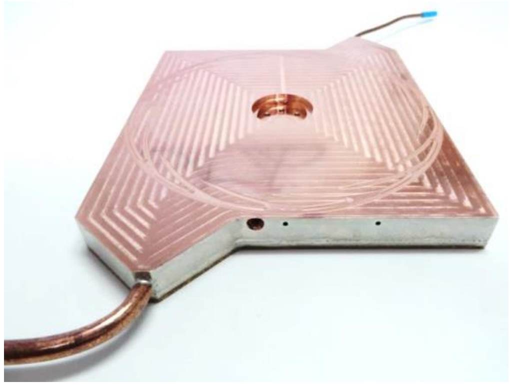
Awards/Recognition: N/A

Lessons Learned:
- Baseplate design may result in cost increase
- Increased air flow rate require special accommodation

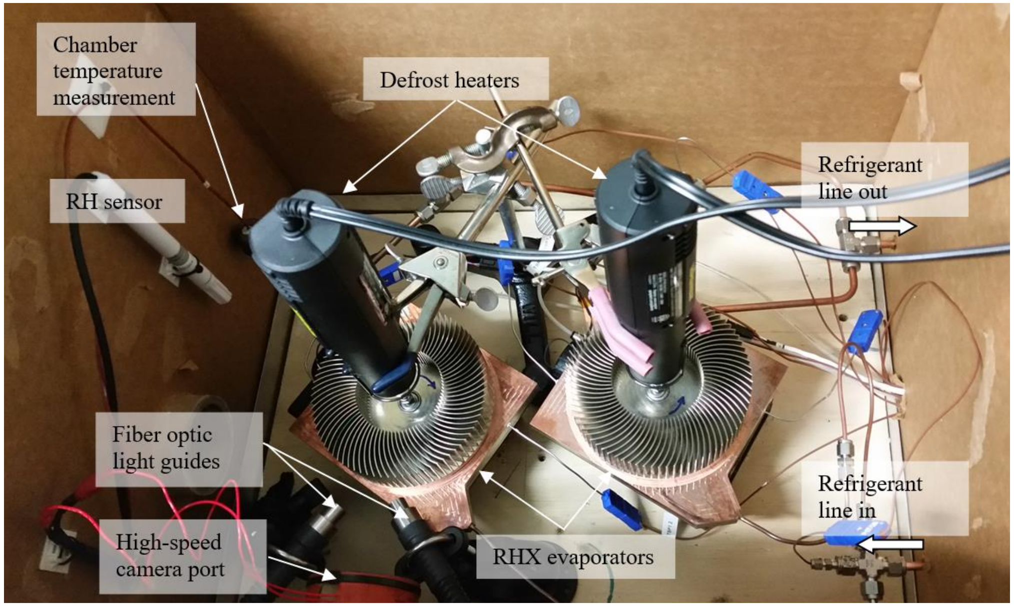
First Generation Prototype

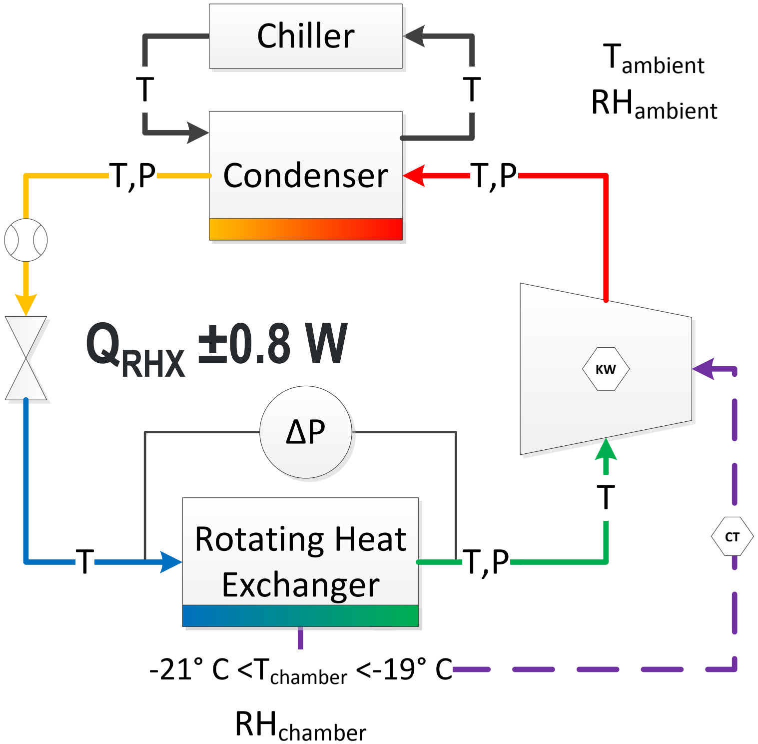
- 5.5” diameter impellers, motors and shafts
  - Adapted from the condenser unit developed in previous SNL/UMD program
  - Provide >100 W of cooling at 1000 rpm
  - 96 cfm air flow
- Custom baseplates with refrigerant channels, air bearing, and motor mount
  - 0.8 mm × 0.8 mm flow channels, 3 passes
- N_2/compressed air for air bearing startup





Week Long Experiment – Experimental Facility





- Compressor cycled to maintain -21°C < $T_{chamber}$ < -19°C
- RHX constantly rotating
- $T_{ambient}$ = 32.2°C (DOE Testing Conditions)

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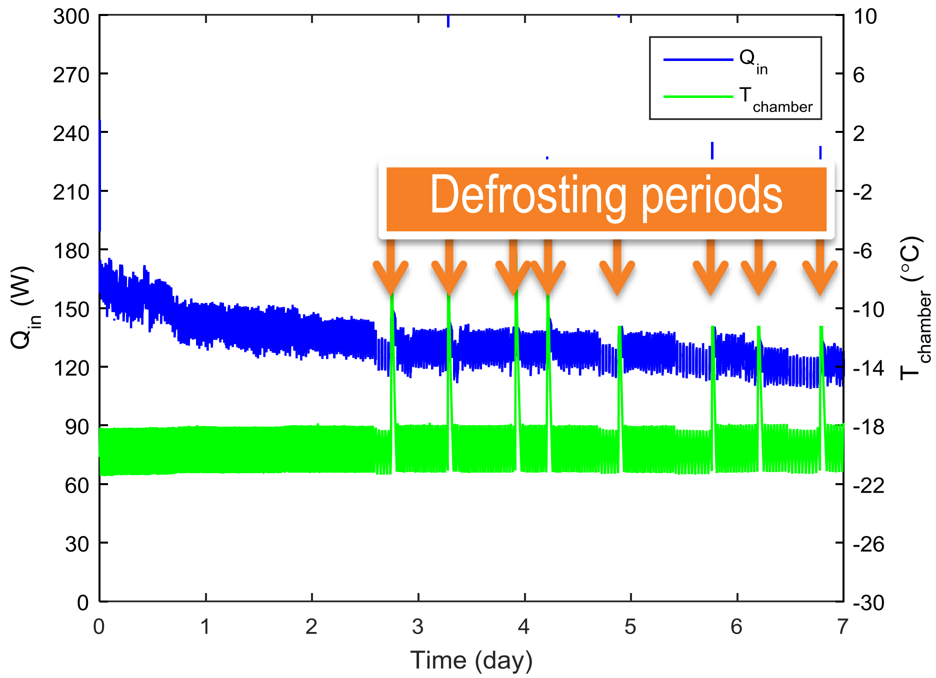
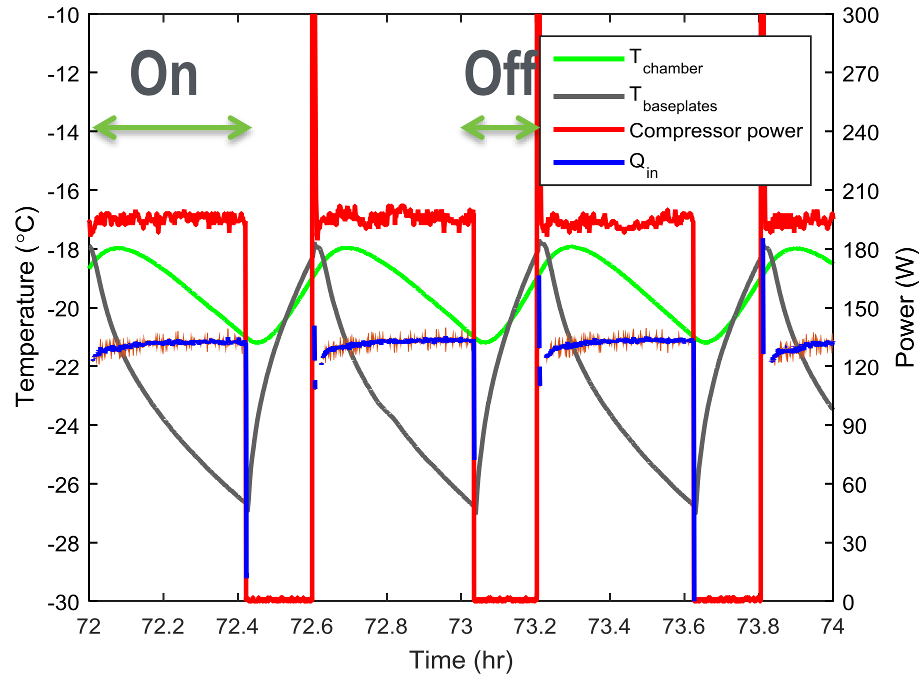
Week-Long Experiment Results





Mass flow rate$_{R134a,ave}$ = 0.78 g/s

$h_{in,ave}$ = 219.8 kJ/kg

$h_{out,ave}$ = 388.3 kJ/kg

-21°C < $T_{chamber}$ < -19°C

-27°C < $T_{baseplates}$ < -18°C

$$Q_{ave} = \dot{m}_{R134a} \Delta h_{RHX} = 131.4 \text{ W}$$

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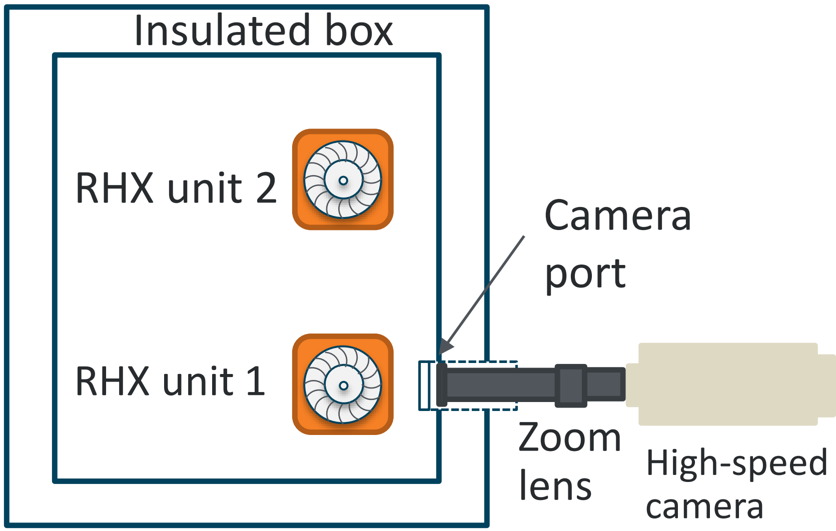
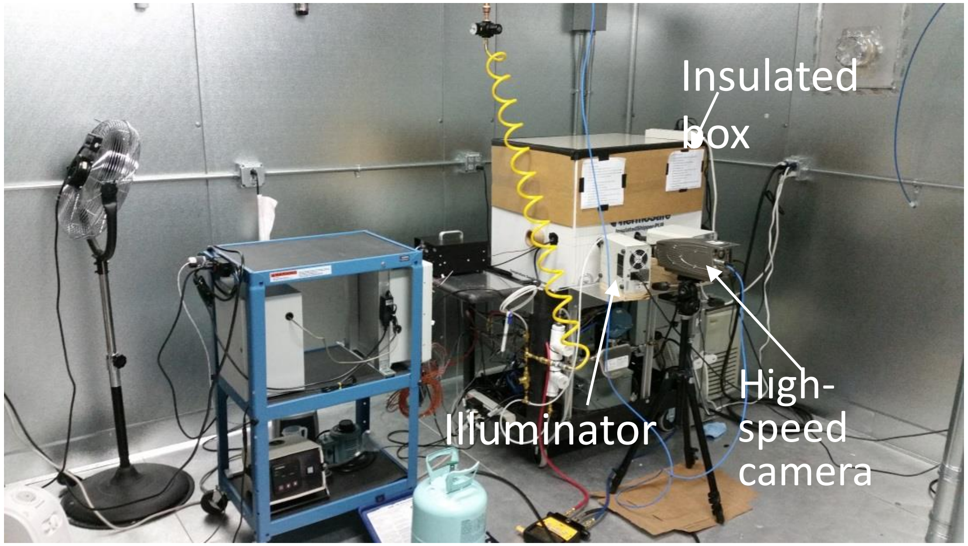
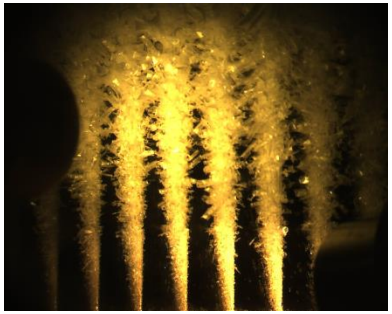
Frost Study

- The high-speed camera setup allowed for capture of frost growth on the entire fin height



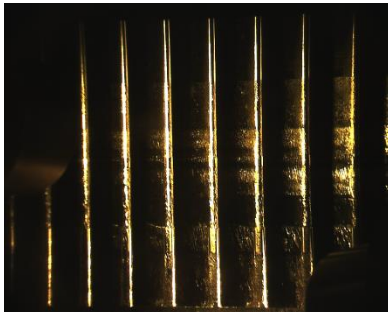


Stationary Impellers; 53 hrs.



hour 53:14

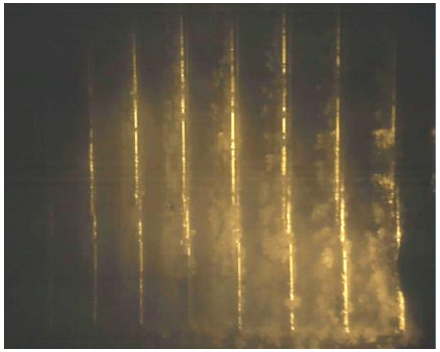
Cycling Impellers; 49 hrs.



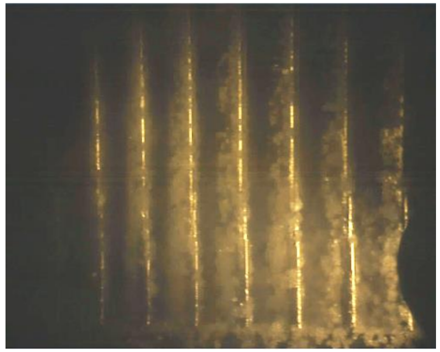
hour 49:16

Frost Study Results

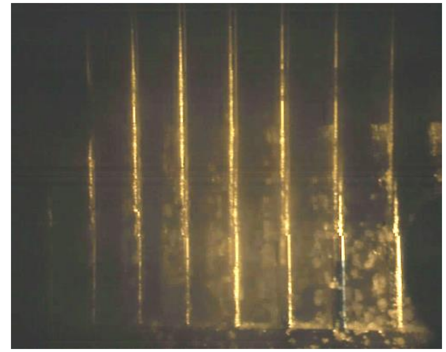
Day 3, Hour 6



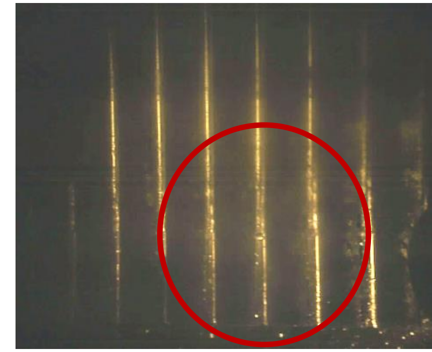
Day 3, Hour 21



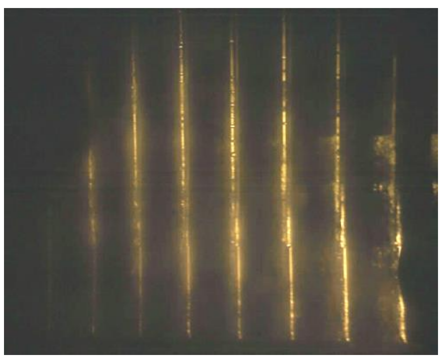
Day 6, Hour 4

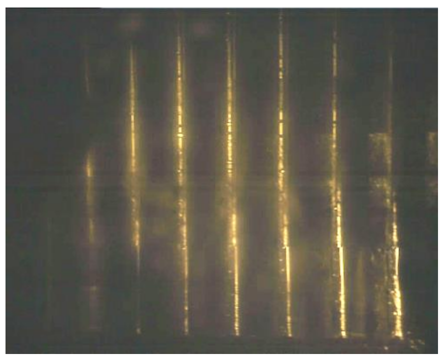


During defrost

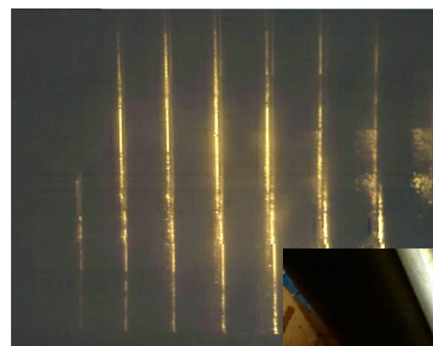


After defrost

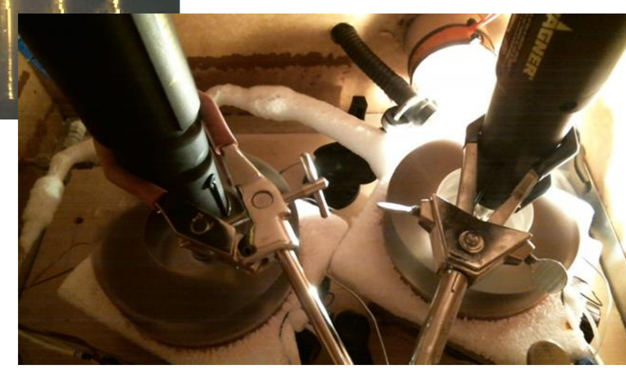




After defrost



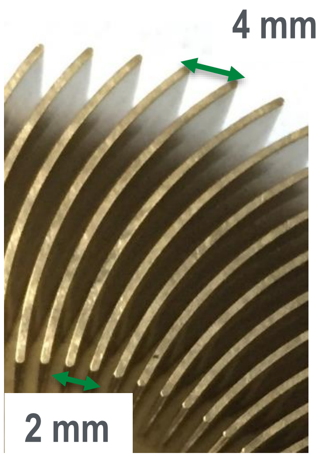
Note water droplets



Frost leaves as solid particles at freezer temperature; as such the evaporator inlet subcooling can be greatly enhanced

Frost Study - Conclusions

- Rate of frost growth on RHX is much slower than on conventional HX
  - Large air flow rate
  - Centrifugal forces
- Defrosting of RHX is much faster than conventional HX
  - Desirable to be frost particle removal – need defrost process optimization
  - Easy water shedding capability
- Geometric limitation on frost thickness and airflow
  - Inner spacing determines maximum frost thickness
  - Frost growth impacts CFM
  - Tradeoff between number of fins (higher surface area) and fin spacing (longer period of time before defrost)



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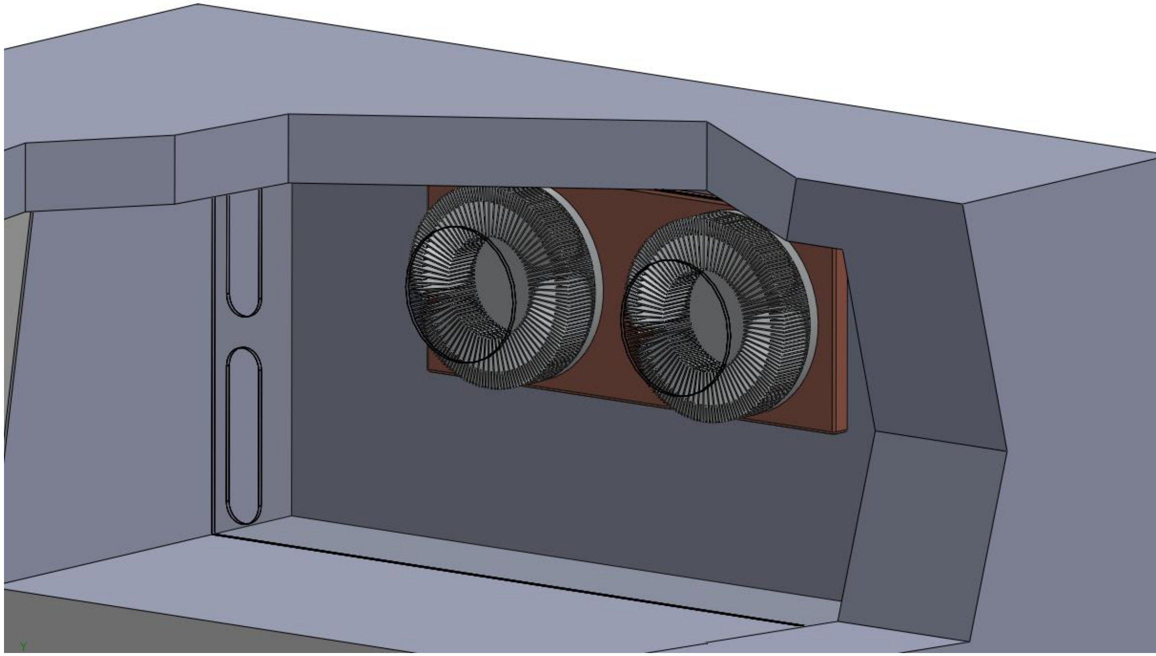
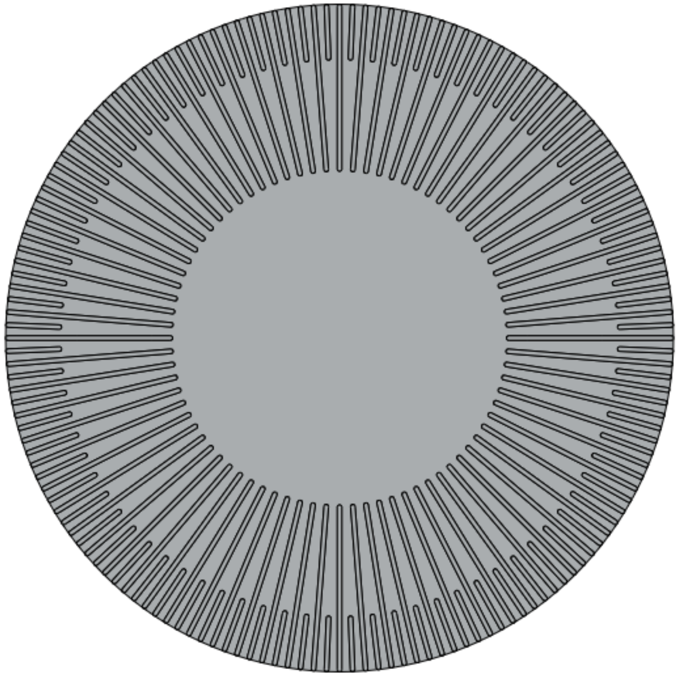
Second Generation Prototype

- Vertically mounted in freezer compartment, in place of conventional evaporator
- Frost-resilient, high performance heat-sink-impeller design





- 165 mm diameter heat-sink-impellers (2)
- 1000 rpm
- 0.036 K/W thermal resistance with 9 W of input power
- > 0.35 ft^3 savings in freezer compartment

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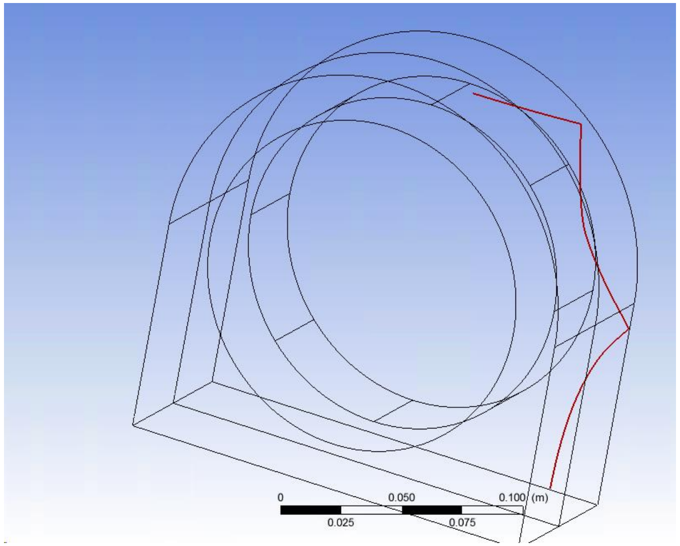
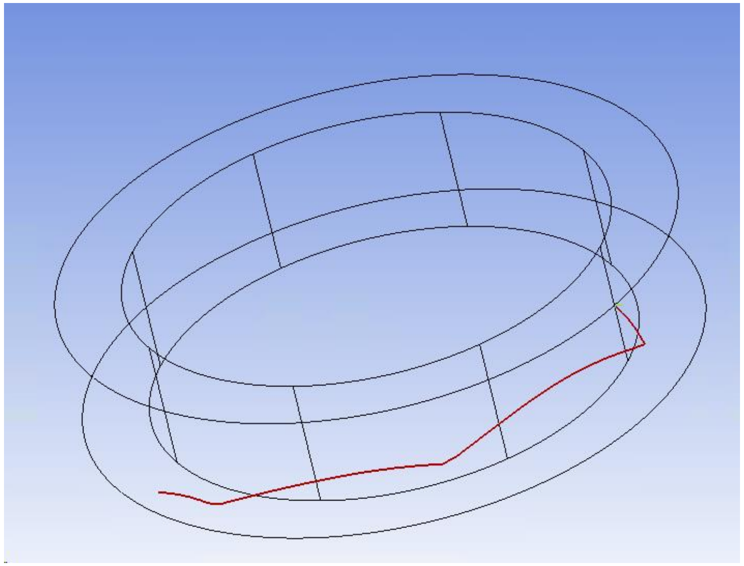
Frost Collector Design

- Goal: to design a frost collector that can effectively separate frost particles from supply air flow using minimum volume
- Method:
  - Commercially-available Computational Fluid Dynamics (CFD) tools were utilized to simulate the RHX air flow
  - Discrete Phase Method (DPM) was enabled to study the interaction of solid (frost) and air flow and predict the particle trajectory
  - The collision impact between collector and frost were considered by inputting coefficient of restitution
- Research Procedure:
  - General study on particle trajectory prediction for RHX
  - Propose candidate design(s)
  - Optimize selected design

Frost Collector Design – General Study on Trajectory



Frost trajectory of vertically placed impeller



Frost trajectory of horizontally placed impeller

- Particle typically stays in the frost collector for less than 0.1 seconds for horizontally placed impeller and up to 0.14 seconds for vertically placed impeller
- Larger density (>=50 kg/m3) and larger size (diameter >= 1cm) frost particles' trajectory is greatly affected by gravitational force
- Small frost tends to be airborne

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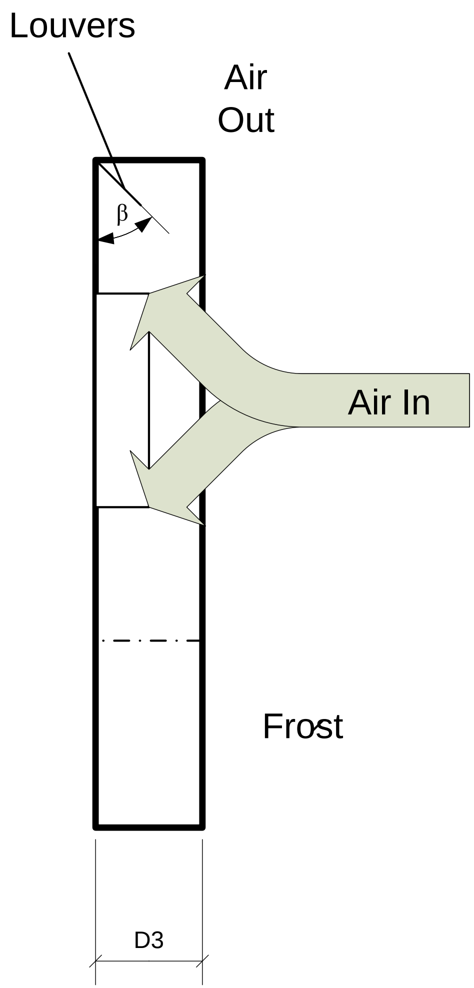
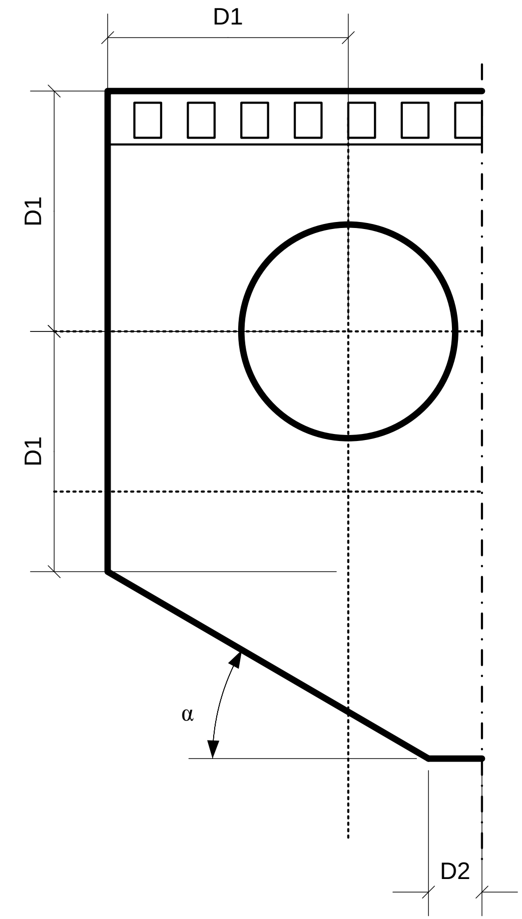
Frost Collector Design – Design Optimization

- Objectives: minimize volume and minimize frost accumulation in the collector

- Optimization parameters:
  - D1
  - D2
  - D3
  - α
  - β





Project Integration and Collaboration

Project Integration: partnership between ORNL, SNL, and UMD

- SNL performed previous studies on market potential; appliance and equipment outreach; and provided samples and prototypes for evaluations
- ORNL and UMD have a historic partnership and strong industry collaboration. ORNL and UMD reached out to several of the appliance manufacturers and provided them with some information on benefits of this new technology

Communications:

- Work presented at the ASHRAE Winter Conference 2016
- Frost study will be presented at the ACEEE Summer Study Conference 2016

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Next Steps and Future Plans

Next Steps and Future Plans:

- Continue planned project activities:
  - Integrate frost collector
  - Fabricate and integrate second generation prototype
  - Run 1-month long un-interrupted experiment to evaluate longevity
- Future design with 1 impeller design (cost, integration)
- Reach out to appliance and equipment manufacturers in order to find pathways to eventual commercialization
  - Use project results as stepping stones for CRADA negotiation
- Disseminate knowledge

REFERENCE SLIDES

Project Budget

Project Budget:
- Federal funds:
  - ORNL: $475,477
  - SNL: $245,000
  - UMD: 175,000
- Cost Share (University of Maryland): $99,500

Variances: NA

Cost to Date: (02/29/2016)
- ORNL: $390,583
- SNL: $209,000
- UMD: $99,512 (Federal) + $56,418 (Cost Share)

Additional Funding: NA

Budget History					
FY 2015 (past)		FY 2016 (current)		FY 2017	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$651k	$99.5k	0	0	NA	NA

Project Plan and Schedule

Project Start: 10/01/2014		Completed Work
Projected End: 09/30/2016		Active Task (in progress work)
		Milestone/Deliverable (Originally
		Milestone/Deliverable (Actual)

Task	FY2015 Q1 (Oct-Dec)	FY2015 Q2 (Jan-Mar)	FY2015 Q3 (Apr-Jun)	FY2015 Q4 (Jul-Sep)	FY2016 Q1 (Oct-Dec)	FY2016 Q2 (Jan-Mar)	FY2016 Q3 (Apr-Jun)	FY2016 Q4 (Jul-Sep)
Past Work								
Preliminary Design Specification								
Baseplate Design								
Fabrication of prototype								
Go/No-Go Decision: unit run for 1 week uninterrupted								
Market Assessment								
Current/Future Work								
Design Frost Collector								
Design and Integrate 2nd generation prototype								
Operate 2nd Generation prototype for 1 month uninterrupted								