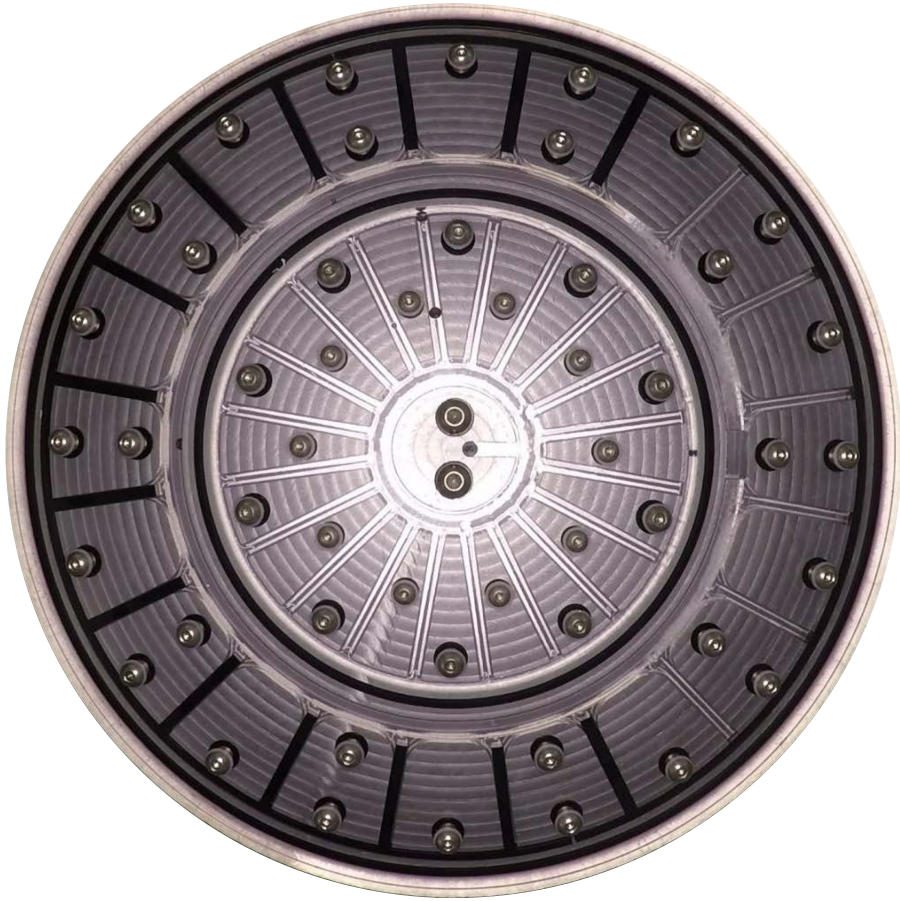
# Rotary Vapor Compression Cycle (RVCC)

2017 Building Technologies Office Peer Review



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

**Arthur Kariya,** Sandia National Laboratories
hakariy@sandia.gov

# Project Team

Sandia National Laboratories

Arthur Kariya, PhD

Wayne Staats, PhD

Jeff Koplow, PhD

cts

Scott Wujek, PhD

Stefan Elbel, PhD

Pega Hrnjak, PhD

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

# Project Summary

**Timeline**:

Start date: September, 2014

Planned end date: February, 2017

Key Milestones

I. Characterize refrigerant flow patterns in rotating frame (May 2016)
II. Characterize air-side heat transfer enhancement in the rotating frame (May 2016)

**Budget**:

**Total Project $ to Date**:

- DOE: $774,000
- Cost Share: $86,000

**Total Project $ :**

- Same as above

**Key Partners**:

Creative Thermal Solutions

Urbana, IL

**Project Outcome**:

This exploratory project will assess the viability of the RVCC concept, which can lead to substantial energy savings in the future. The following questions will be answered:

1. Does the vapor compression cycle operate in the rotating frame? What are the characteristic attributes in the rotating frame?
2. How much air-side heat transfer enhancement can be achieved in the rotating frame?

# Purpose and Objectives

**Problem Statement:** The efficiencies of vapor compression cycles (VCCs) are currently limited by heat exchanger performance and compressor energy requirements

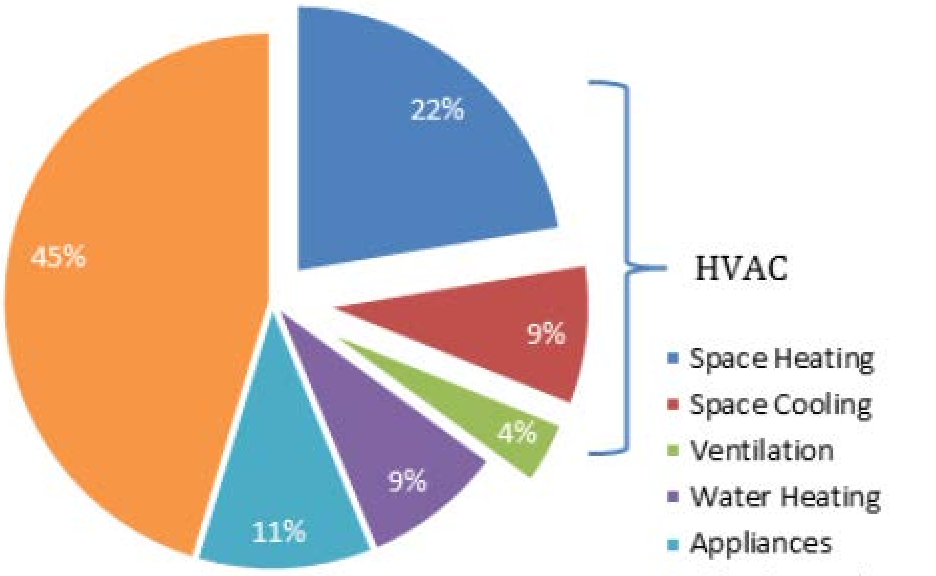
**Target Market and Audience**: Space heating and cooling comprises **31%** of total energy consumption in the residential and commercial sectors (12 Quads)[1,2]. We propose a technology (RVCC) that can potentially reduce energy consumption by **21%**.

**Impact of Project:**
First step in developing a new rotating vapor compression cycle topology for energy efficiency

- Assessment of refrigerant flow characteristics in the rotating frame
- Assessment of air-side heat transfer in rotating frame

**Future Goal (4+ years):**
Development of prototype for commercialization

Primary energy consumption in the residential and commercial sectors[2]




1. http://www.eia.gov/oiaf/aeo/tablebrowser/
2. BTO Multi-Year Program Plan

# Approach

**Approach**: Our previous development of the rotating heat sink (Patent US8228675) has shown that heat transfer is enhanced in the rotating frame. Here, this approach is adapted to a larger scale for VCCs, where the evaporator and condenser are rotated.

**Distinctive Characteristics**: The entire vapor compression cycle is rotated. Unique experimental methods are developed.

**Key Issues**:

Refrigerant-side characterization

*Does the vapor compression cycle operate in the rotating frame? What are the characteristic attributes in the rotating frame? Is there potential of heat transfer enhancements in the rotating frame?*

Air-side heat transfer:

*How much air-side heat transfer enhancement can be achieved in the rotating frame?* The rotating heat evaporator and condenser must be smaller than stationary heat exchangers.

Manufacturability

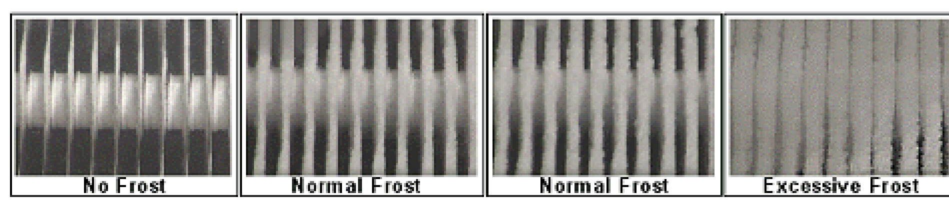
*Can the RVCC topology be economically manufactured at scale?*

# Inherent Inefficiencies in Vapor Compression Systems

Fouling of evaporator coil[3]

Broken connecting rod from liquid ingestion in compressor[4]

Frosted evaporator in cold climates[5]




Progression of evaporator frosting[6]

3. www.bakerhomeenergyconsultant.org
4. www.danfoss.com
5. www.hvac-talk.com
6. www.appliance 411.com

# Rotary Vapor Compression Cycle (RVCC)

Sandia Rotating Heat Sink

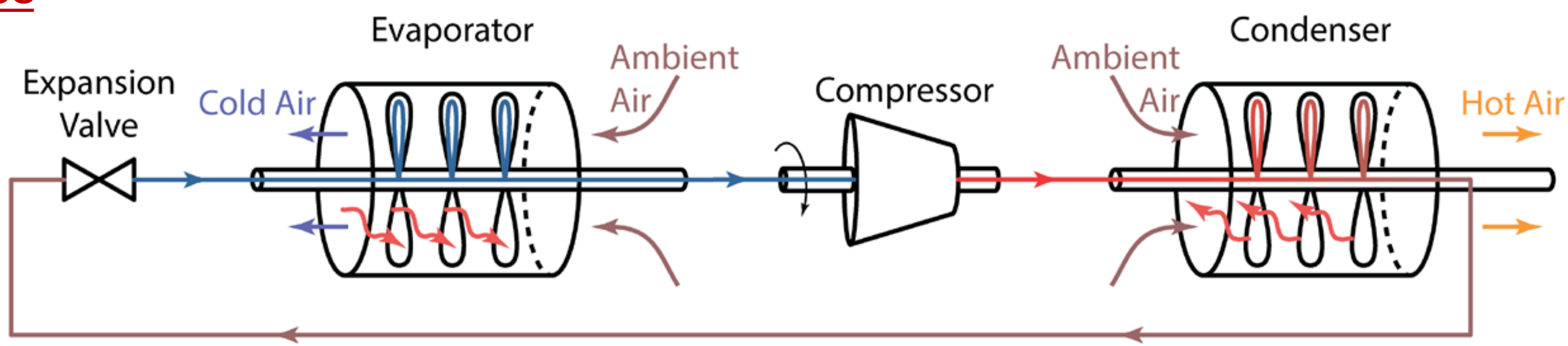
Method of reducing inefficiencies in vapor compression systems

- Enhanced air-side heat transfer
- Immunity against fouling
- ~~Centrifugal/Coriolis phase separation~~

- Centrifugal phase separation

- Enhanced air-side heat transfer
- Centrifugal phase separation

RVCC




Note: In actual device, all refrigerant lines reside in central shaft.

# CHARACTERIZATION OF REFRIGERANT FLOW

GOALS:

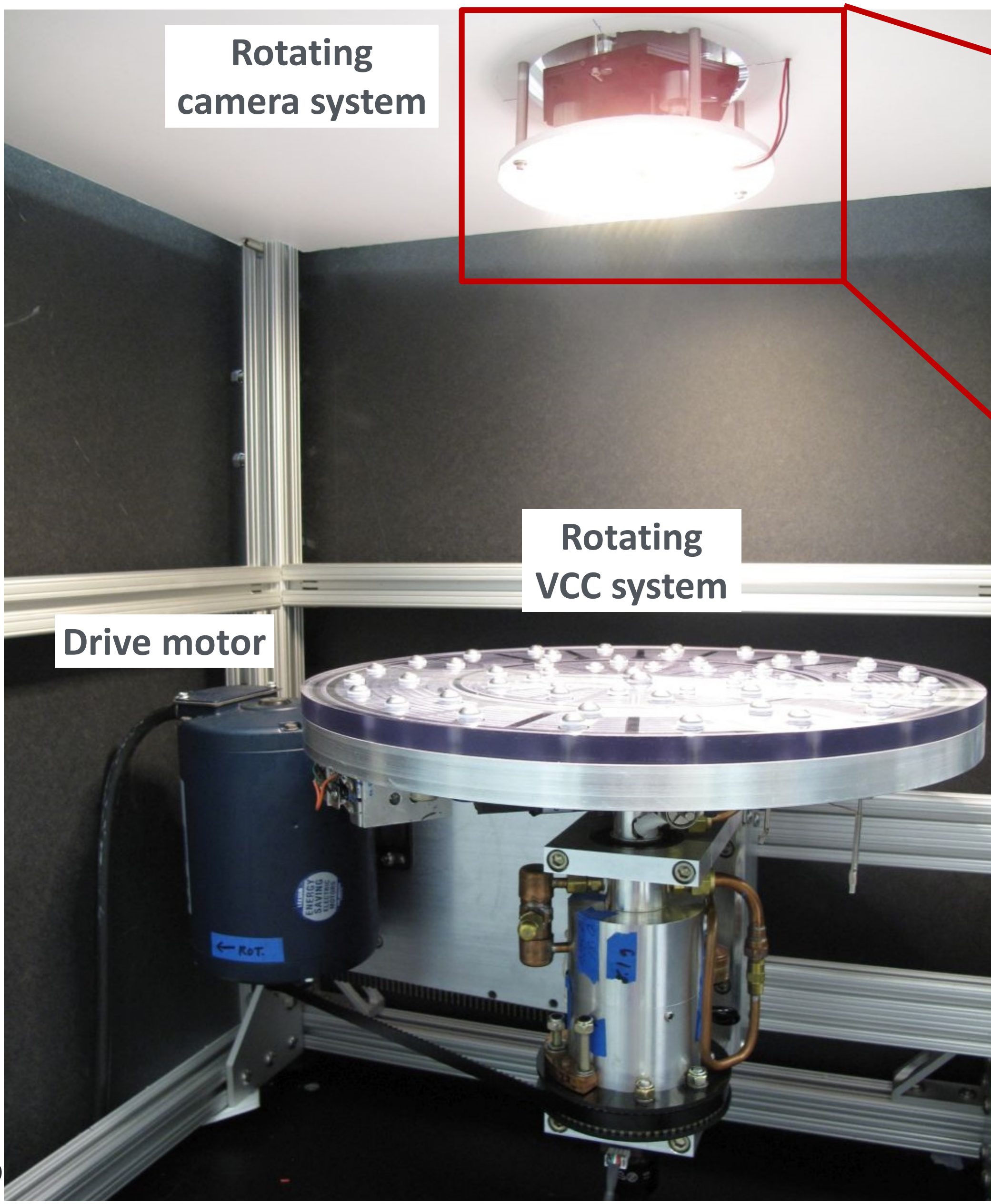
1) Assess axisymmetry of refrigerant flow

2) Characterize liquid/vapor phase separation and flow characteristics in the rotating frame

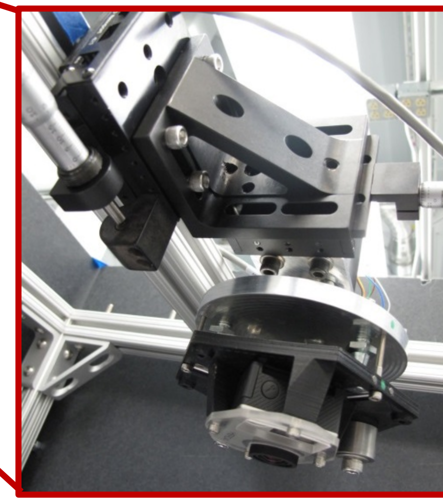
Methodology

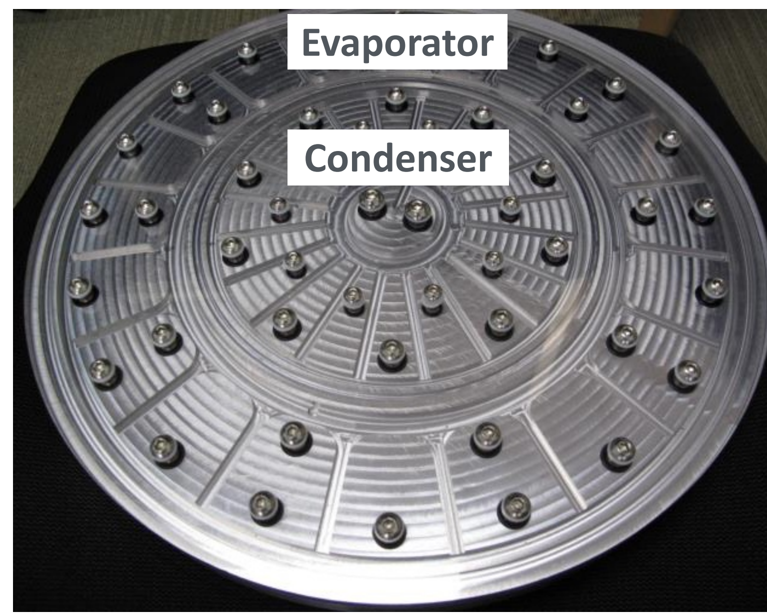
- Develop a system to visually study phase change and flow patterns in the rotating frame
  - Having the complete refrigeration cycle in the rotating frame eliminates the need to channel fluids into/out of rotation
  - Phase change behavior in channels will be viewed through transparent window
- Design a co-rotating camera system to film flow phenomena

# Refrigerant Visualization Experiment

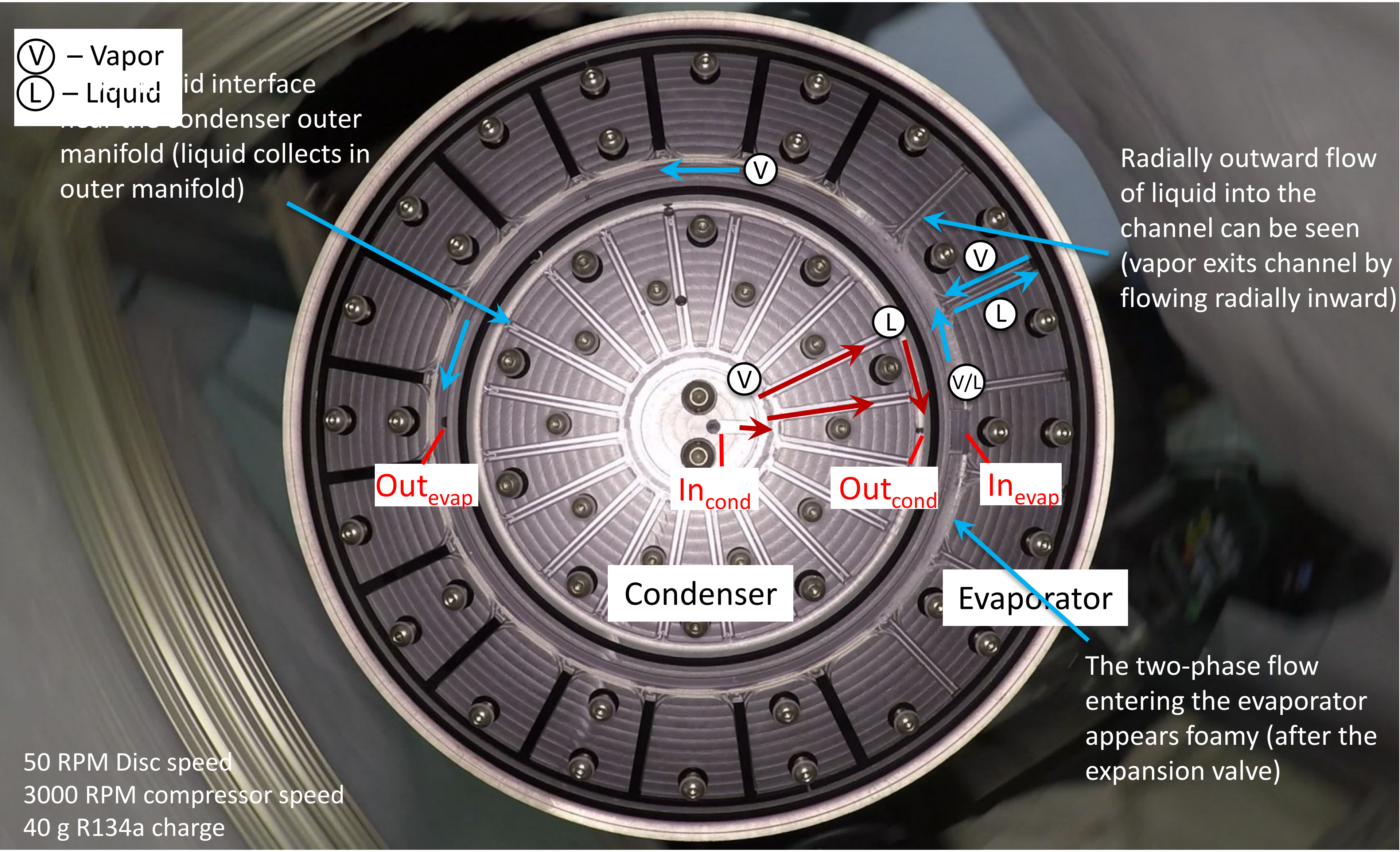



Detail view of rotating camera system





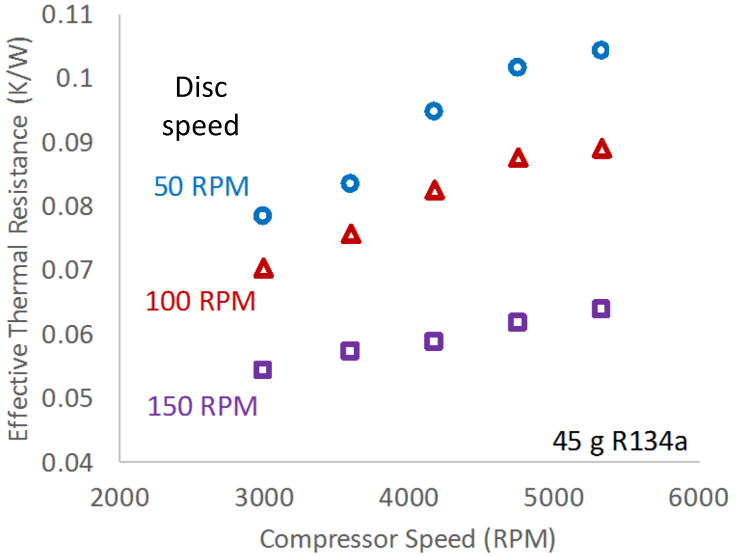
# Flow Pattern in Condenser and Evaporator

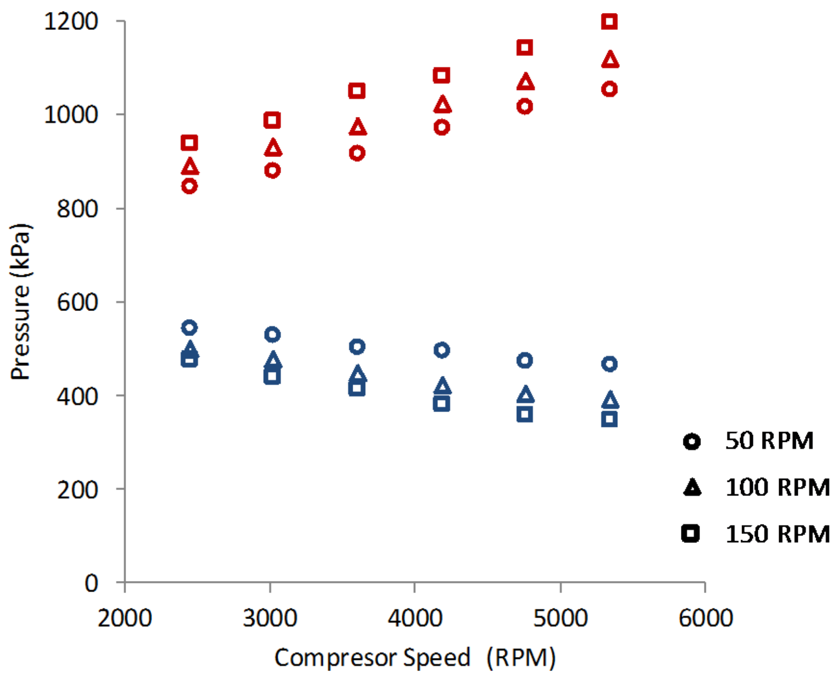


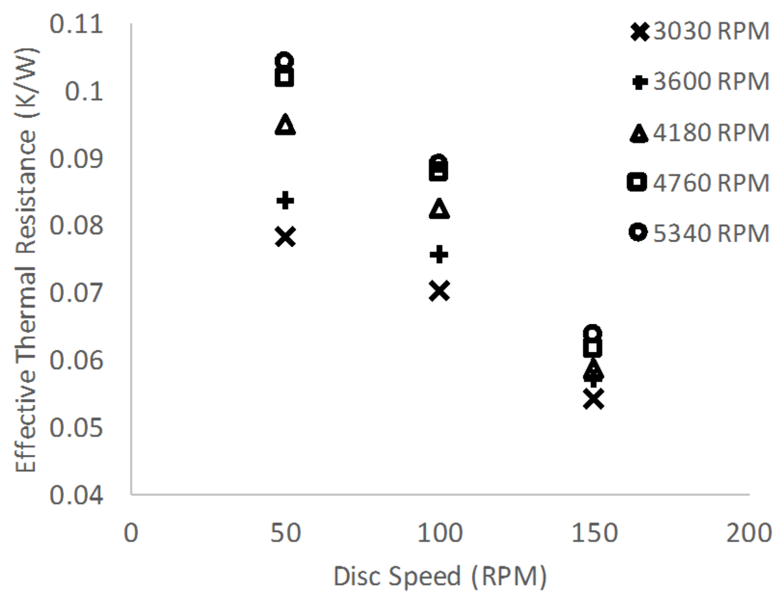
# Operating Characteristics

- As compressor speed increases, $P_{COND} - P_{EVAP}$ increases
  - Thermal resistances increase
  - Matches operating characteristics predicted in fixed orifice VCCs
- As disk speed increases, thermal resistance decreases

$$Effective\ Thermal\ Resistance = \frac{T_C - T_E}{Q_E}$$

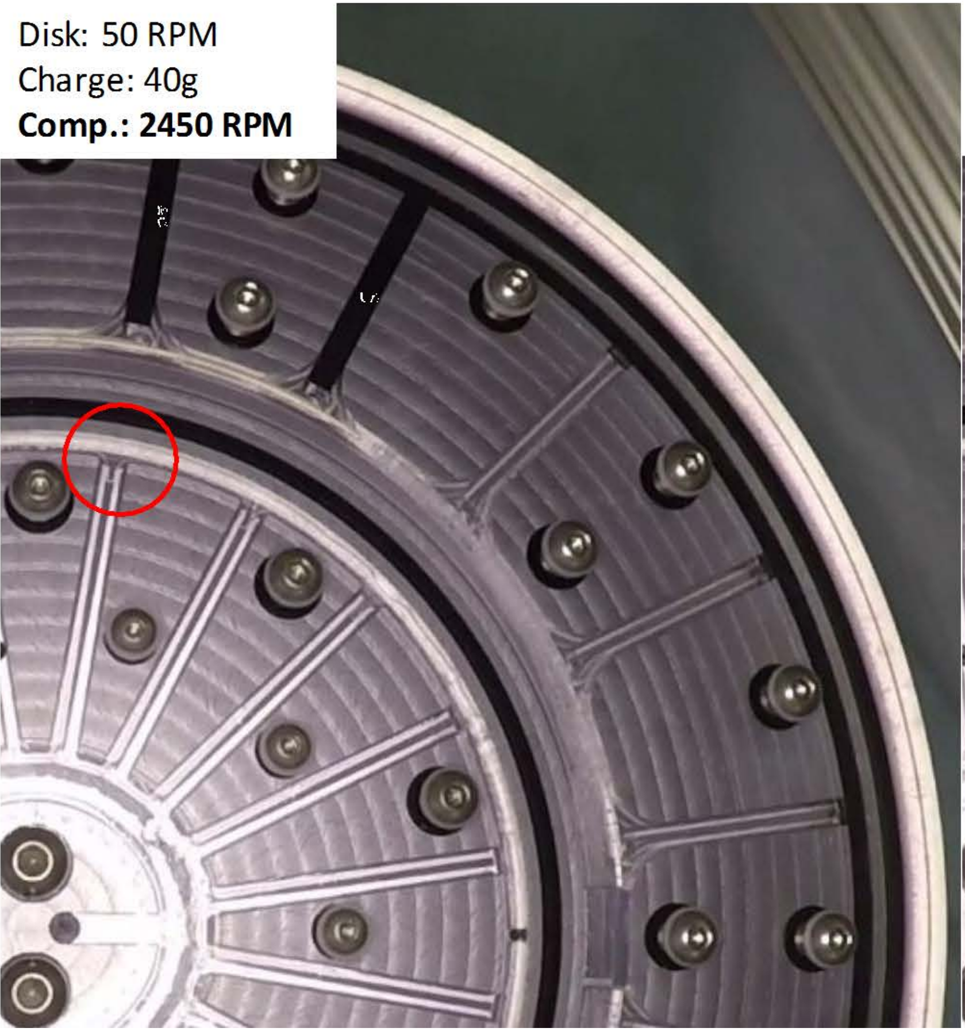


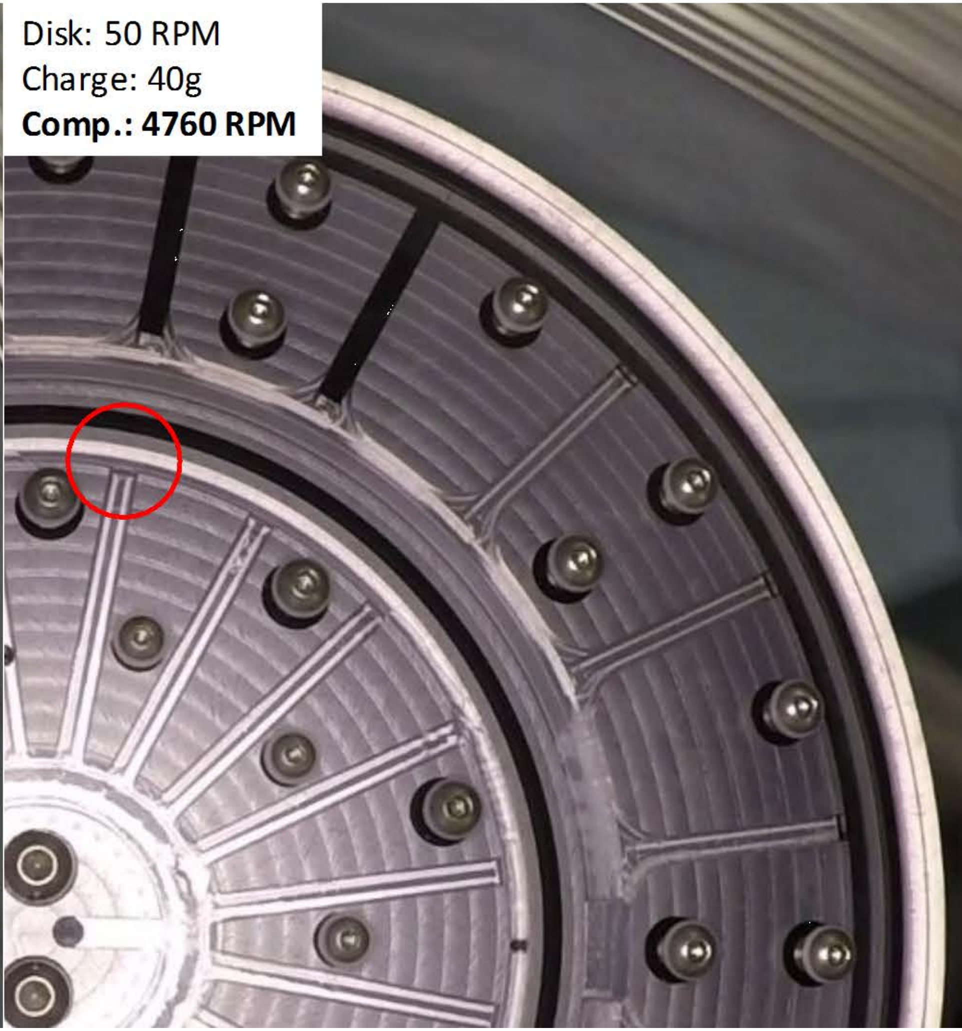



# Liquid Distribution

- Change in thermal resistance reflected in liquid distribution
- Issues: axisymmetry and channel space utilization



# CHARACTERIZATION OF AIR-SIDE HEAT TRANSFER

GOAL:

- Characterize the heat transfer coefficient (HTC) on a rotating surface so that the required heat transfer area can be determined for RVCC application

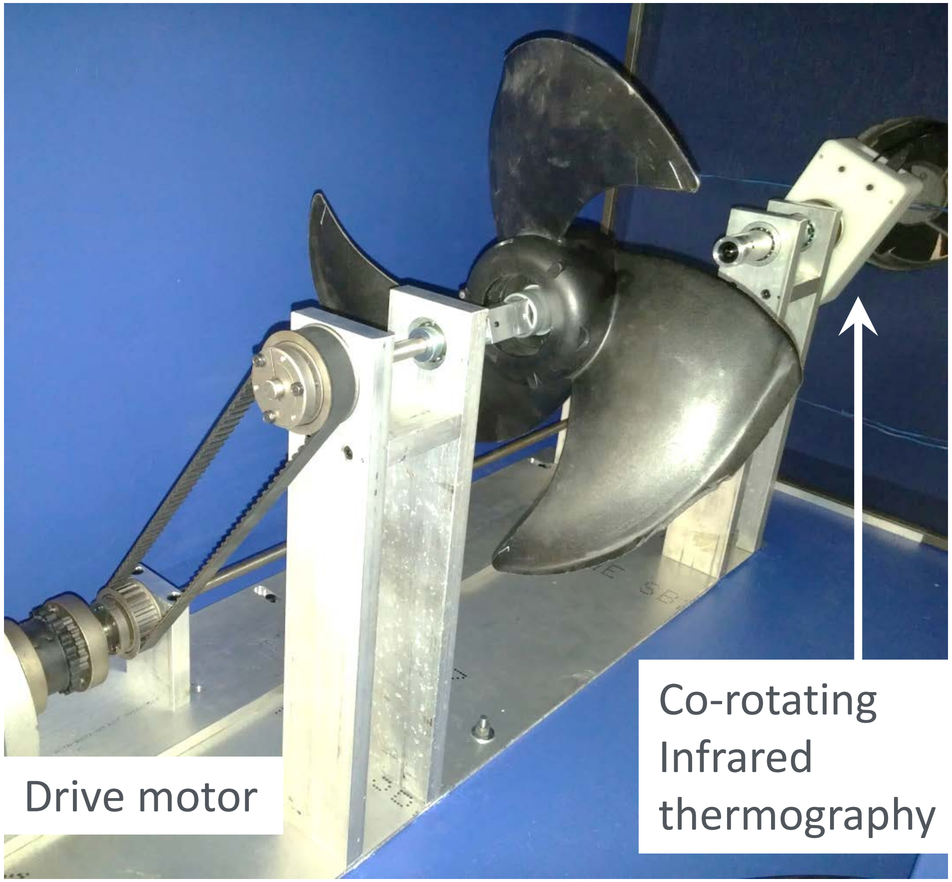
Methodology

- Experimentally measure HTC for commercially available fan blades as upper bound prediction
  - Compare to HTC for non-rotating flat plate with similar air-flow velocity to assess HTC enhancement in rotating frame
- Characterize HTC via transient cool-down tests

$$HTC = f(location\ on\ blade,\ RPM)$$

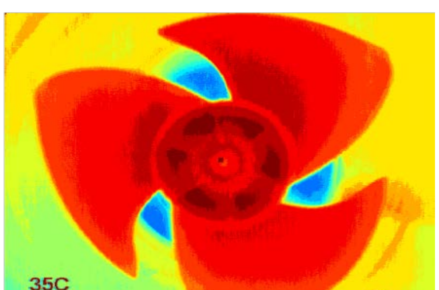
  - Determine HTC scaling characteristics with radius and RPM

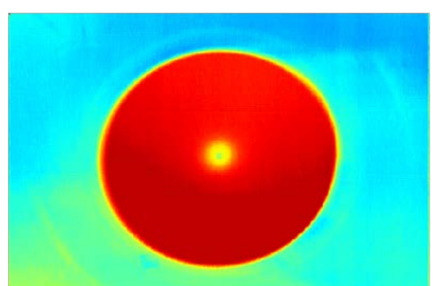
# Air-side Convective Heat Transfer Experiment

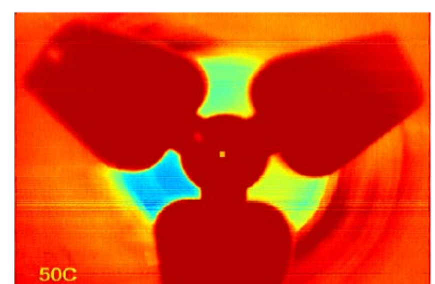



## Non-intrusive infrared thermography

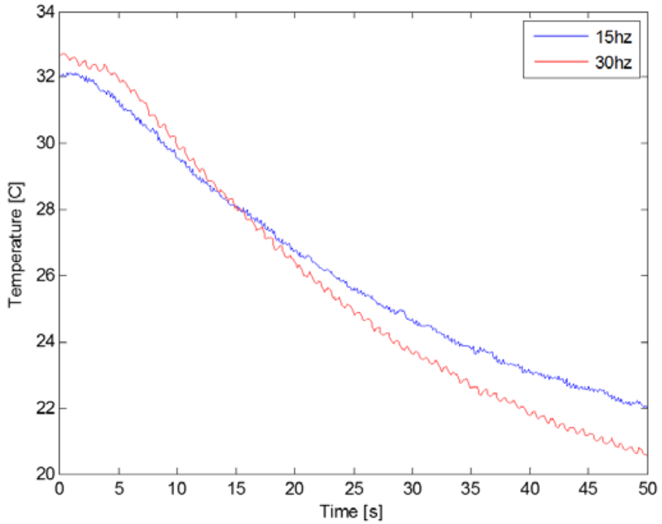
- No instrumentation on rotating heat transfer body (no rotating wires)
- Allows simple measurement of different heat transfer bodies (inexpensive and fast)
- Measures transient temperature response

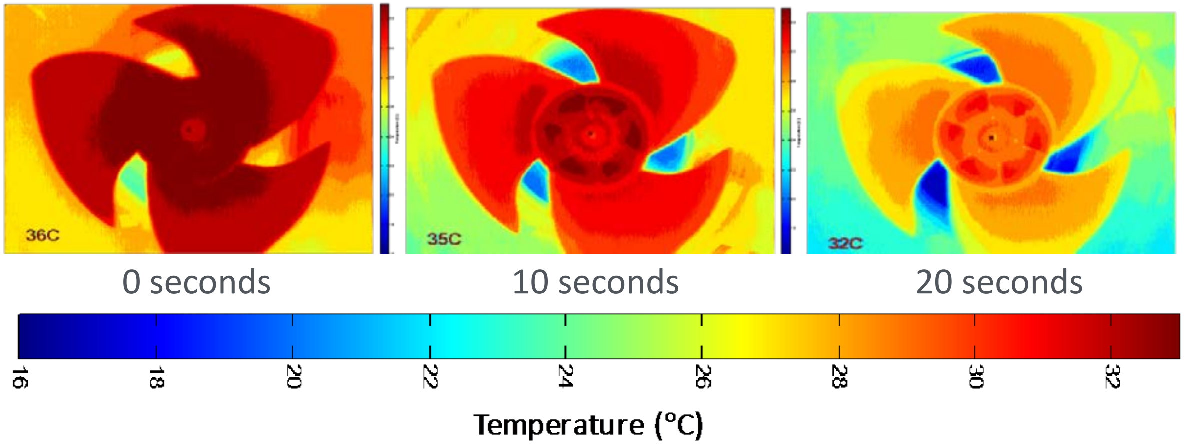




# Transient Cooling test




When

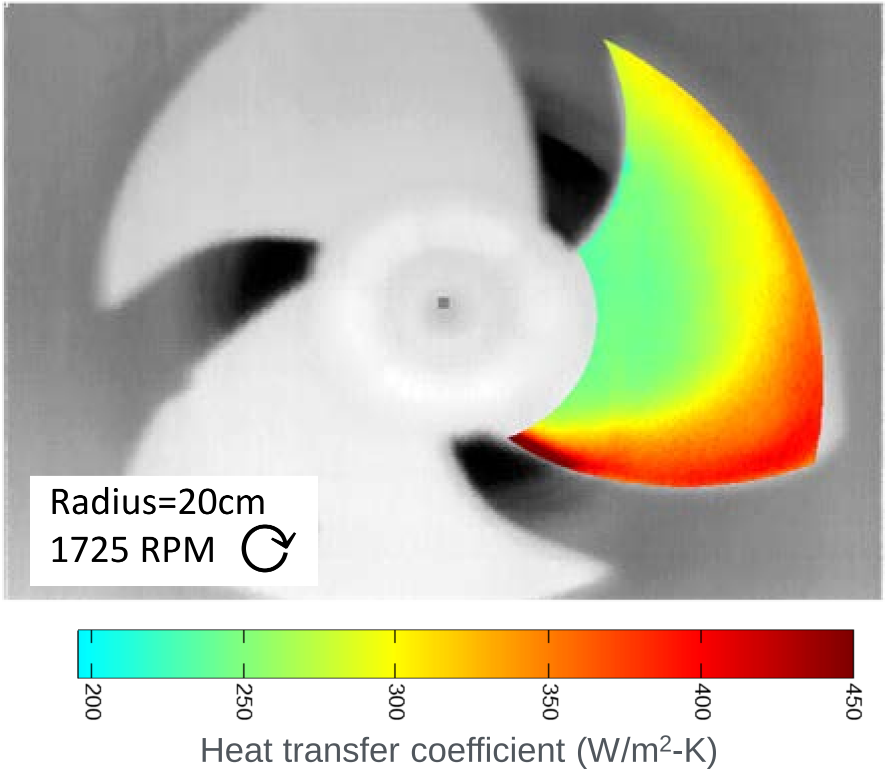
$$Fo > 0.2$$

Thermal response characterized by:

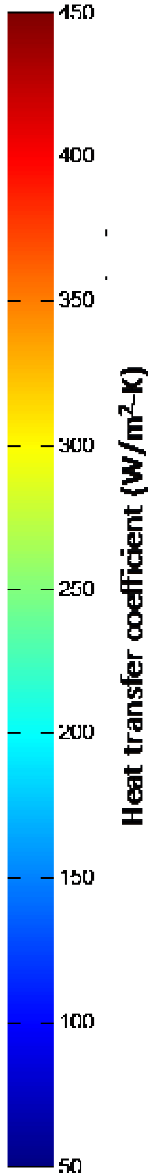
$$\frac{T - T_\infty}{T_o - T_\infty} = \frac{4 \sin \zeta_1 \cos\left(\zeta_1 \frac{x}{L_{half}}\right)}{2\zeta_1 + \sin(2\zeta_1)} e^{-\frac{\zeta_1^2 \alpha t}{L_{half}^2}}$$

Where $\zeta$ is an eigenvalue of the expression:

$$\frac{\mathbf{h}L}{k} = \zeta_n tan\zeta_n$$

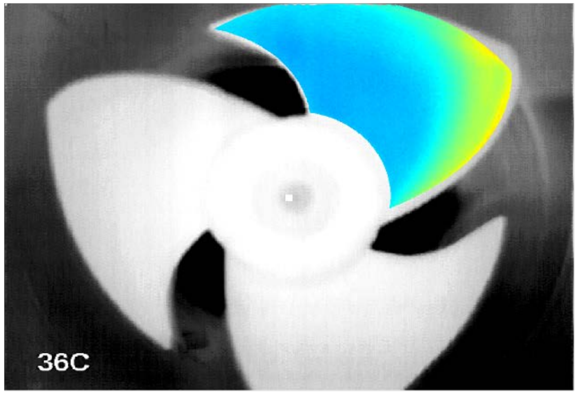


# Heat Transfer Coefficient

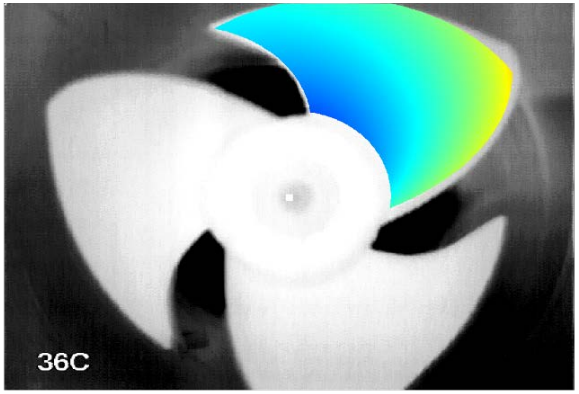



Using experimental data, a non-dimensional expression was developed to predict the local heat transfer coefficients

Experimental Data (1150 RPM)




Empirical Prediction (1150 RPM)

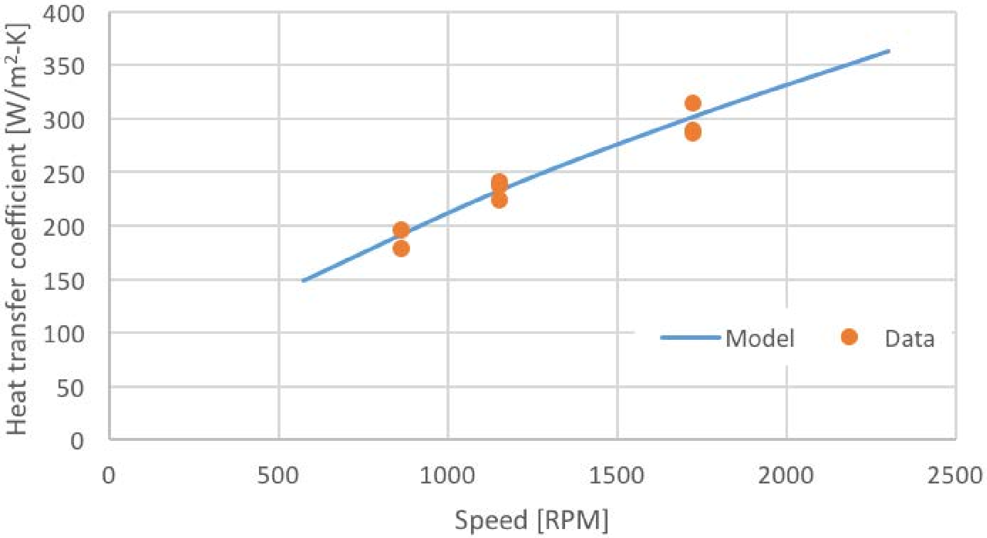



Reynolds number exponent (0.64) is greater than that for laminar flow (0.5), despite the absence of transition to turbulent flow

- Indicates heat transfer enhancement

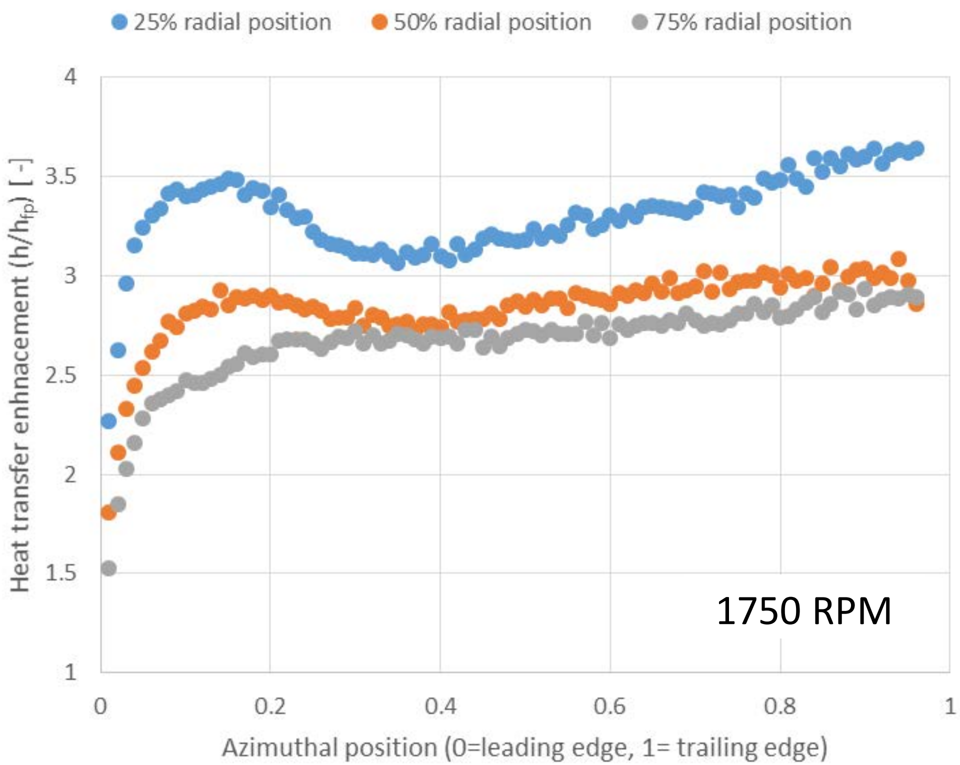
$$Nu_L = 0.906 Re_L^{0.64}$$

Average heat transfer coefficient

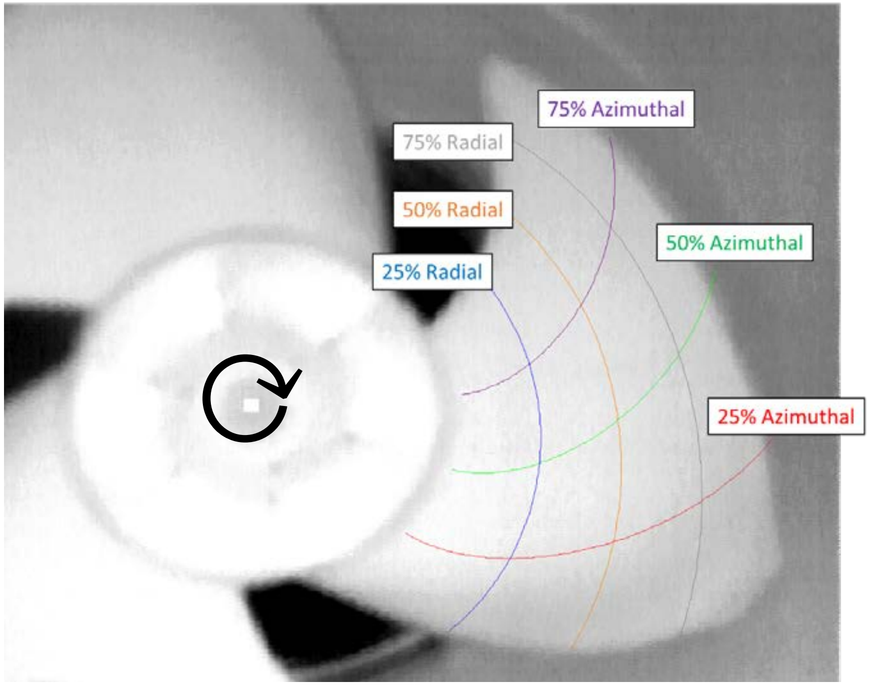


# Heat Transfer Enhancement in the Rotating Frame

- 250%-350% improvement in heat transfer coefficient achieved in the rotating frame




(Distance from leading edge)




Leading edge

# Progress and Accomplishments

**Accomplishments**:
1) Patent application filed with follow-on: 4/857,652
2) A de-rotated imaging apparatus was developed for in-situ IR thermography of rotating heat transfer surfaces. 2-3 fold increase in heat transfer coefficient was achieved in the rotating frame.
3) A rotating VCC was developed for investigating phase change behavior in the rotating frame. Proper operation of the VCC and centrifugal phase separation were confirmed.

**Lessons Learned**:
1) Evaporator channel space will be best utilized by a pressure-driven radial flow
2) High centrifugal acceleration limits the axisymmetry of the two-phase flow entering the evaporator
3) Heat transfer enhancement can be best exploited by using more short-chord blades

**Market Impact**:
Measured impact (heat transfer enhancement) is substantial, and corroborates the RVCC value proposition

**Awards/Recognition**: RVCC concept was granted Sandia internal funds for investigating fundamental phase change phenomena in the rotating frame

# Project Integration and Collaboration

**Collaborators**: Creative Thermal Solutions took the lead on the air-side heat transfer studies.  They have experimental facilities that were perfectly suited for the project.

**Project Integration**: Sandia (technology inventor) has a multidisciplinary team with an extensive background in investigating heat transfer in rotating heat exchangers. CTS has expertise in heat transfer, VCCs and manufacturing.  The two groups have weekly meetings to coordinate efforts and exchange information.

**Communications**: Work was presented at  the International Refrigeration and Air Conditioning Conference (July, 2016)

# Next Steps

Primary issues were de-risked with the current work:

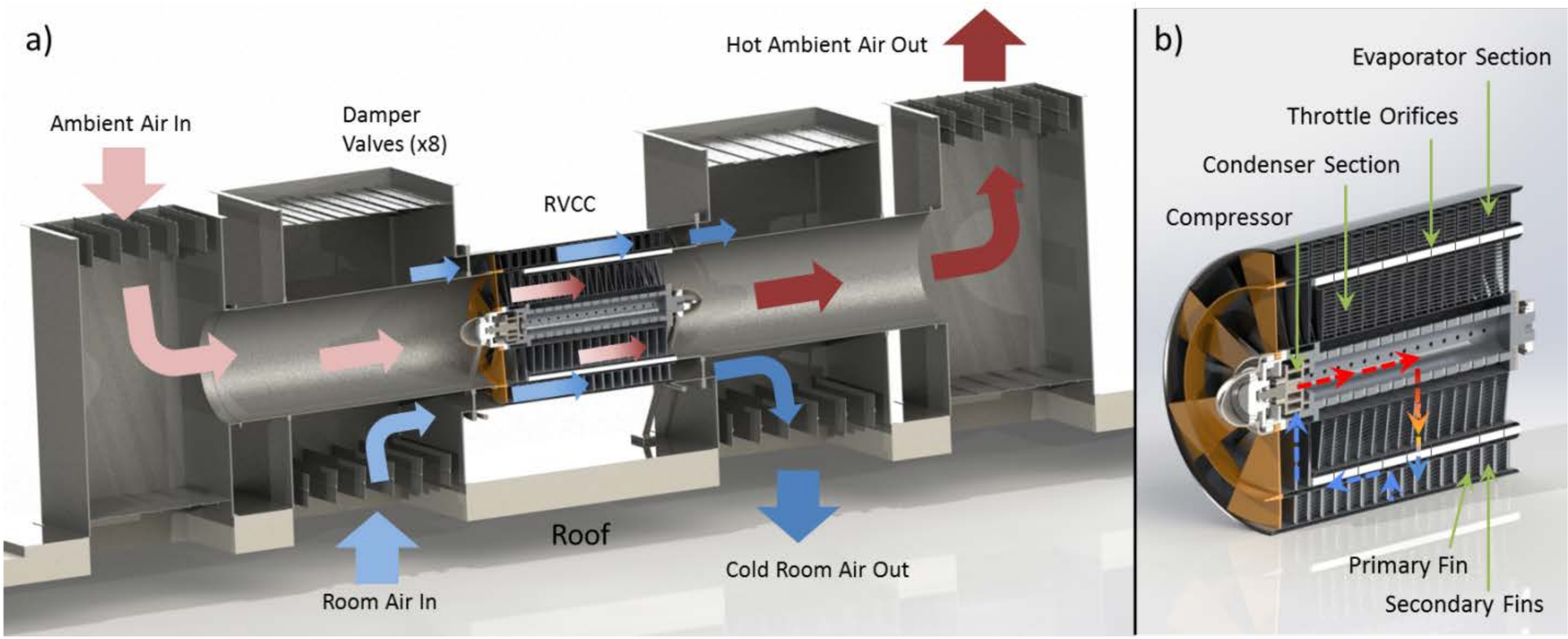
- Proof-of-concept VCC in rotating frame
- Hypothesis testing of refrigerant flow in the rotating frame
  - Effect of centrifugal acceleration, axisymmetry, space utilization
- Characterization of heat transfer enhancement in the rotating frame

Remaining risks to be addressed in future work, which affect implementation:

- Development of an expansion valve with passive feedback
- Manufacturability
- Lubrication management

# REFERENCE SLIDES

# Envisioned Embodiment of RVCC as a Rooftop Unit



# Project Budget

**Project Budget**: $774,000 DOE + $86,000 Cost share
**Variances**: Final report deadline extended to February
**Cost to Date**: $774,000 DOE + $86,000 Cost share
**Additional Funding**: $240,000/year Sandia internal funding for fundamental refrigerant flow investigation

| Budget History | | | |
|---|---|---|---|
| FY 2015 | | FY 2016 | |
| DOE | Cost-share | DOE | Cost-share |
| $380,000 | $43,000 | $394,000 | $43,000 |

# Project Plan and Schedule

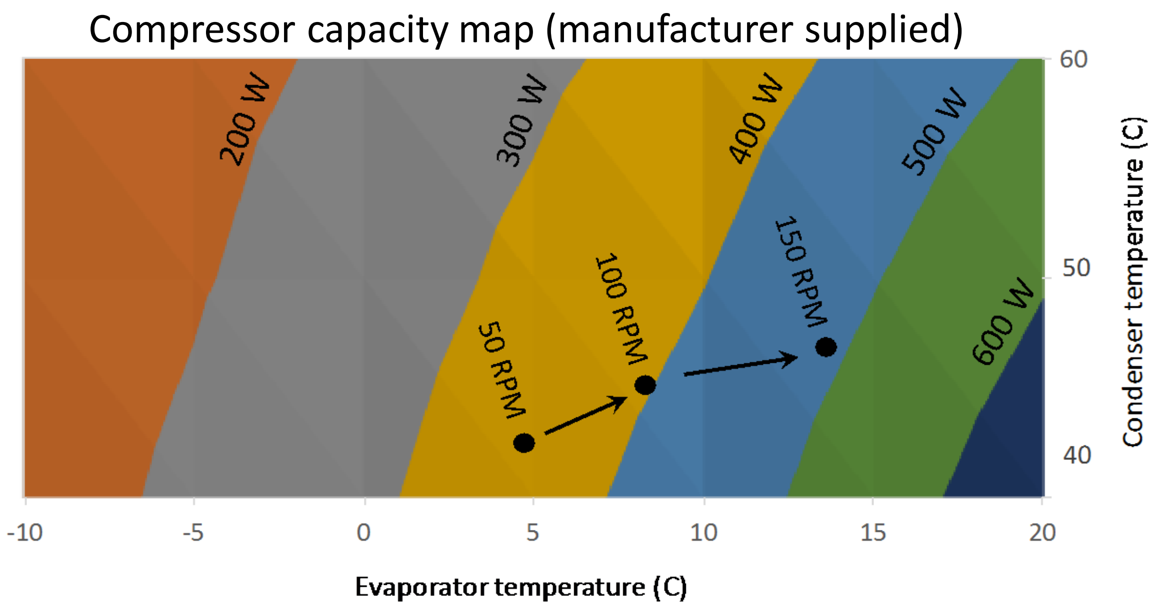
Project details

- Initiation: Sept. 2014 (FY15); End: Feb. 2017
- Ending date (submission of final report) was moved to Feb. 2017 with program manager approval
- Delays encountered in developing rotating imaging (IR, visible light) facilities. Manufacturing assessment and environmental testing was postponed due to the higher priority of the rotating refrigerant flow and air heat transfer studies.  Focus was placed on refining the refrigerant and air experiments.
- Go/no-go decision points:
  - Is there sufficient air-side heat transfer enhancements and refrigerant-side flow benefits in the rotating frame?
  - Does the vapor compression cycle operate as expected in the rotating frame?

| Project Schedule | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project Start: September 2014 | (light blue) | Completed Work | | | | | | | | | | |
| Projected End: February 2017 | (dark blue) | Active Task (in progress work) | | | | | | | | | | |
| | 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** | | | | | | | | | | | | |
| Milestone: Air-side heat transfer study | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| Milestone: Fabricate rotating imaging platform | | | ■ | ■ | | | | | | | | |
| Milestone: Design DAQ system | ■ | ■ | | | | | | | | | | |
| Milestone: Conduct refrigerant flow | | | | | ■ | ■ | ■ | ■ | ■ | | | |
| Milestone: Manufacturing assessment / | | | | | | | | | | | | |
| Milestone: Fabricate and assemble prototype | | | | | ■ | ■ | ■ | ■ | | | | |
| Milestone: Charge assembly with refrigerant | | | | | ■ | ■ | | | | | | |
| Milestone: Test evaporator in frosting | | | | | | | | | | | | |
| Milestone: Write final report | | | | | | | | | ■ | ■ | | |

# Effect of Disc Speed on Temperatures (Pressures)

- The decrease in thermal resistance due to faster disc speed resulted in a higher head load
- In order to increase heat load (mass flow rate), the volumetric efficiency of the compressor had to increase
- This led to an operating point that was higher in temperarture and pressures



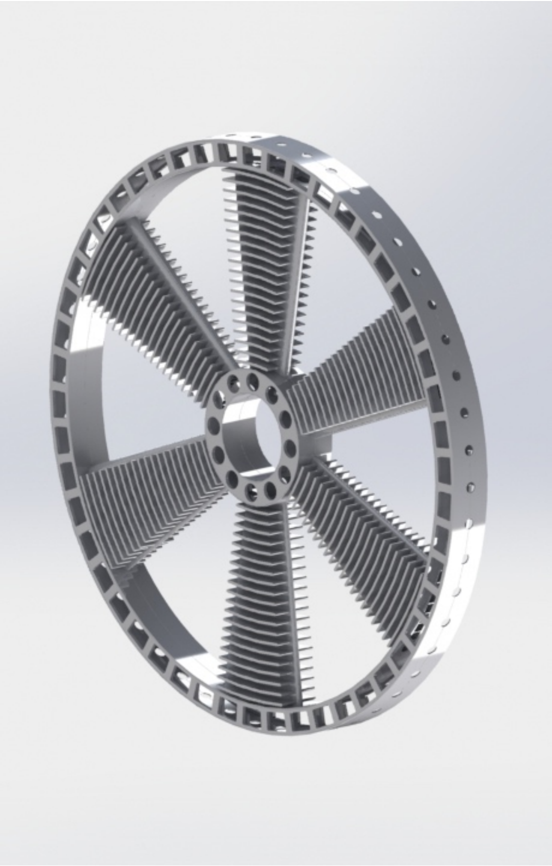

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# Manufacturing

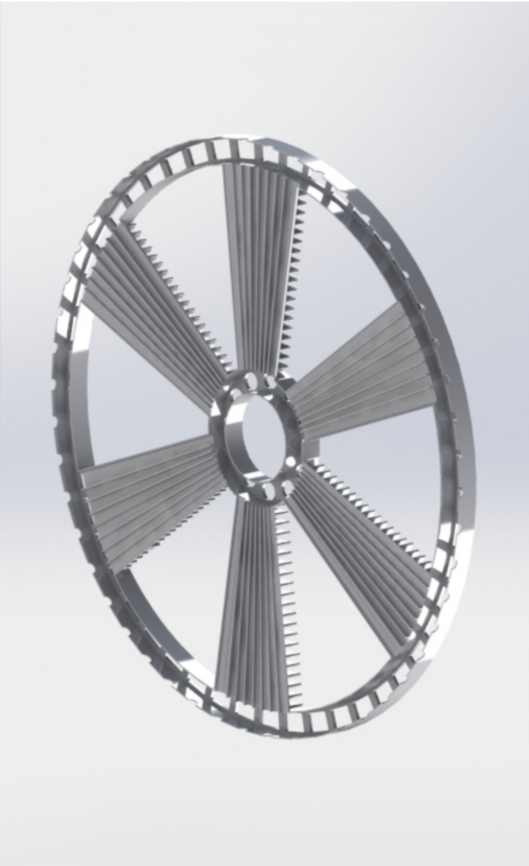
Proposed fabrication:

1) Cold forge parts
2) Resistance projection weld the stack of forged parts

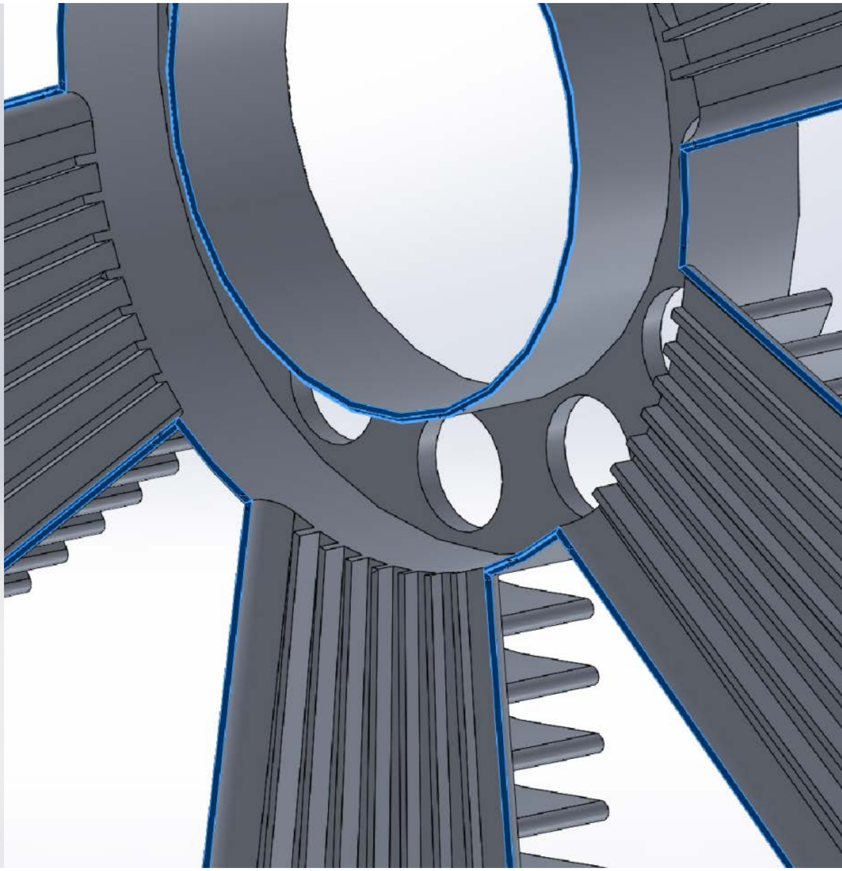
# Manufacturing



Single "layer"



Single "shell"



Close up view of knife-edged weld interfaces (blue)