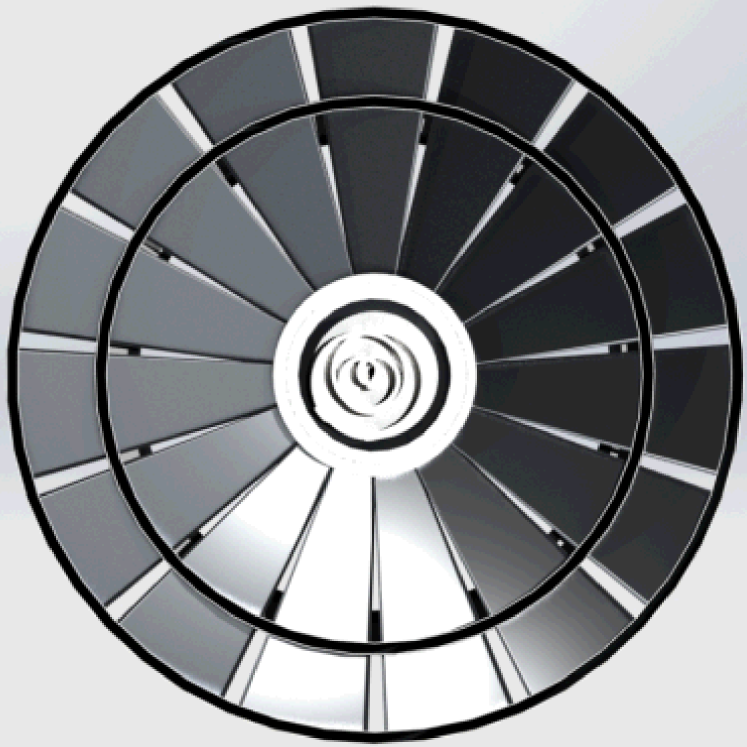
Rotary Vapor Compression Cycle (RVCC)

SAND2016-2714C

2016 Building Technologies Office Peer Review



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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)
III. Assess manufacturability of RVCC topology (Aug. 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. Can the air-side and refrigerant-side benefits in the rotating frame be harnessed for the expected operating conditions?
2. Can the RVCC topology be economically manufactured?

Purpose and Objectives

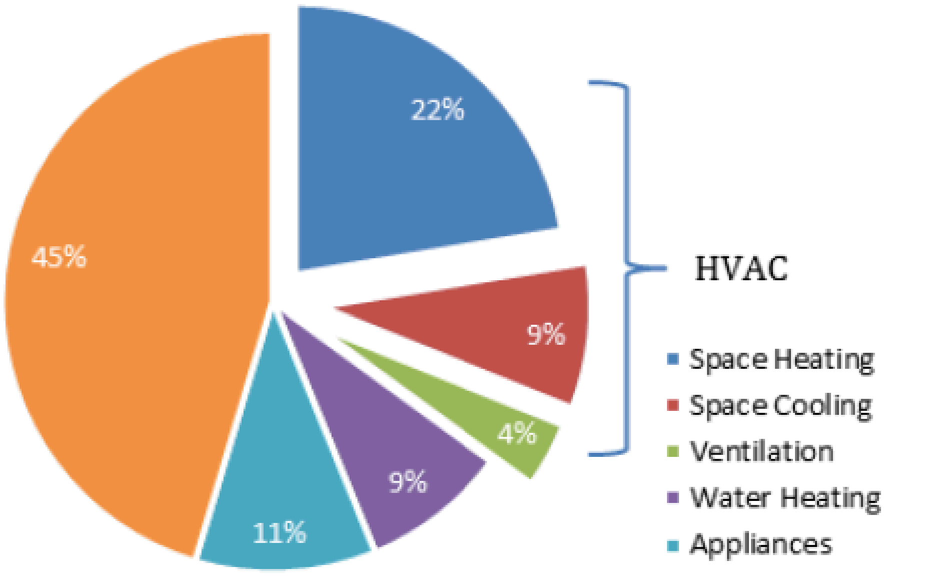
Problem Statement: The efficiencies of vapor compression cycles (VCCs) are currently limited by heat exchanger performance and compressor energy requirements

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 of development of a new rotating vapor compression cycle topology
- Assessment of refrigerant flow and air-side heat transfer in rotating frame
- Assessment of economic manufacturability

Future Goal (4+ years):
Development of 10 kW 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.

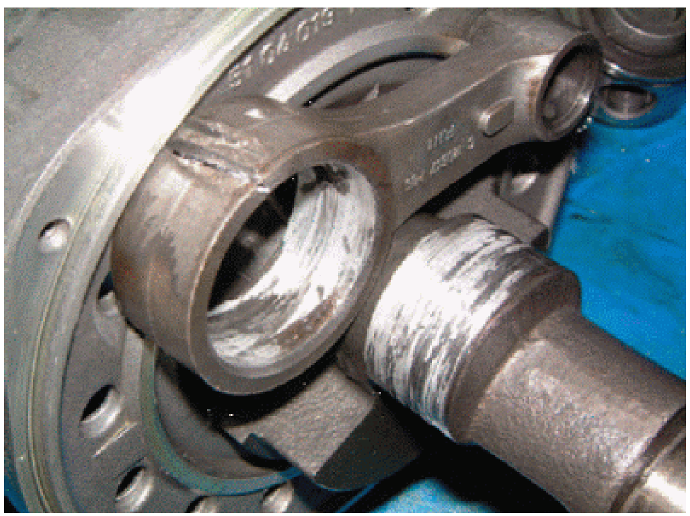
Distinctive Characteristics: The entire vapor compression cycle is rotated

Key Issues:

1) The rotating heat evaporator and condenser must replace sizable stationary heat exchangers; the air-side heat transfer enhancement in the rotating frame must enable the down-sizing of the heat exchangers.
2) The refrigerant inside the evaporator and condenser is rotated. We expect additional refrigerant-side heat transfer enhancements to occur in the rotating frame; this must be investigated.
3) The new topology requires a different manufacturing method; the RVCC must be able to economically manufactured in volume

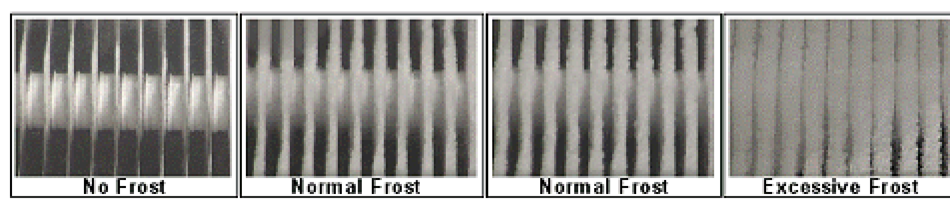
Inherent Inefficiencies in Vapor Compression Systems

Fouling of evaporator coil[3]



Broken connecting rod from liquid ingestion in compressor[4]

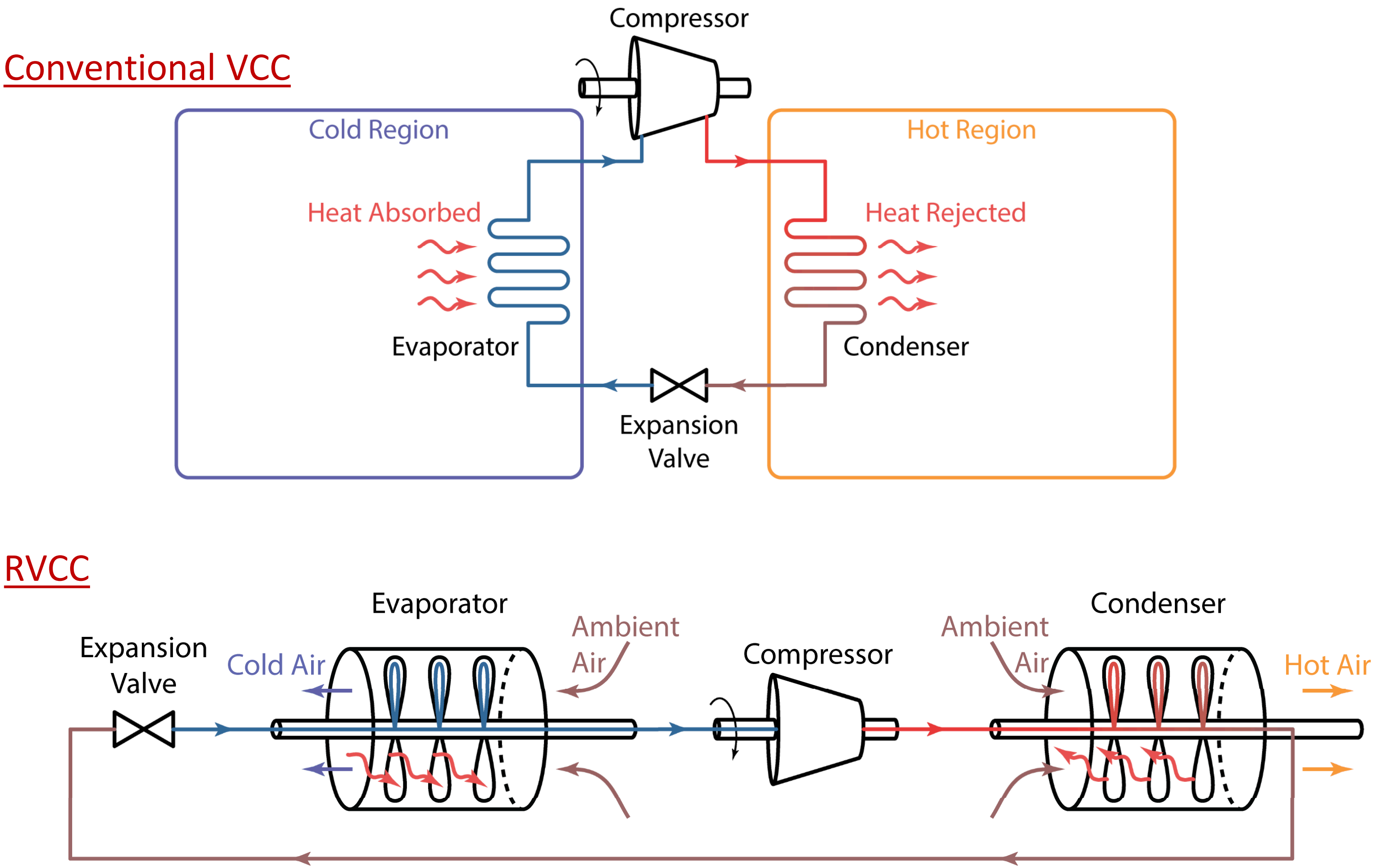
Frosted evaporator in cold climates[5]



Progression of evaporator frosting[6]

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

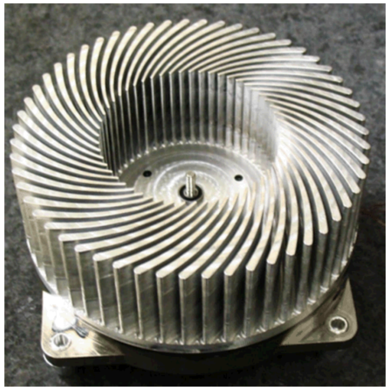
Rotary Vapor Compression Cycle (RVCC)



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

Rotary Vapor Compression Cycle (RVCC)

Sandia Rotating Heat Sink



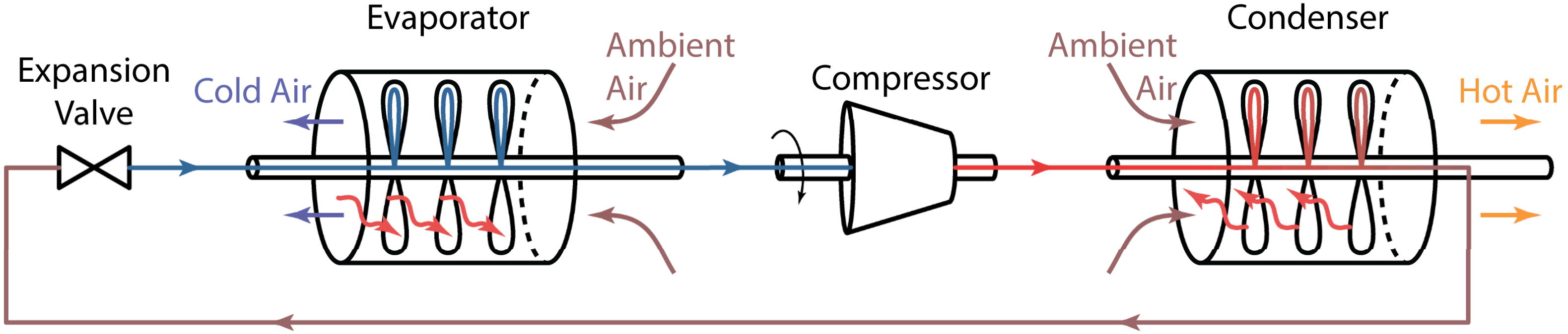
Method of reducing inefficiencies in vapor compression systems

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

- Centrifugal phase separation

- Enhanced air-side heat transfer
- Centrifugal phase separation

RVCC

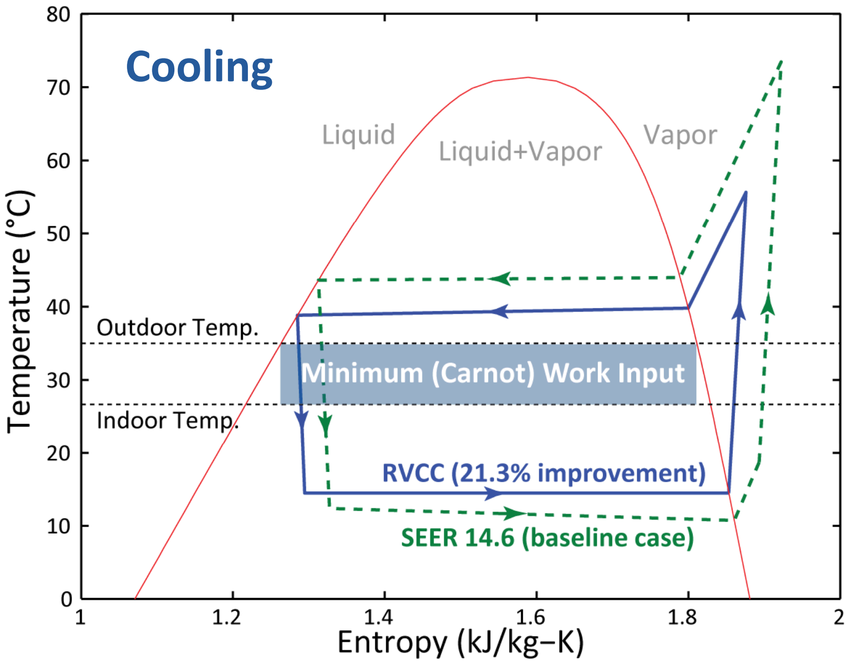


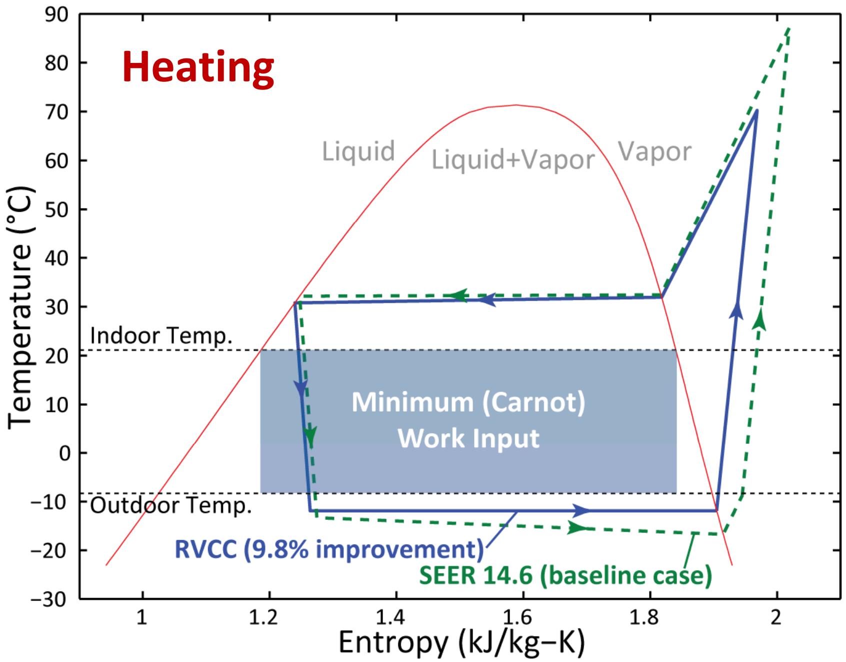
Note: In actual device, all refrigerant lines reside in central shaft.

Predicted Efficiency Improvements

Performance compared to 14.6 SEER heat pump

- Cooling mode: 21.3 % decrease in energy consumption
  - *Elimination of superheat: 4%*
  - *Decreased condenser temperature: 10%*
  - *Increased evaporator temperature: 7%*
- Heating mode: 9.8 % decrease in energy consumption
  - *Elimination of superheating: 5%*
  - *Elimination of defrost cycle: 5%*





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Project Structure

We must answer the following fundamental points for RVCC to be viable:

1) Does the physics work out?

2) Can the RVCC topology be manufactured economically at scale?

CTS

Characterize air-side heat transfer (Experimental)

Confirm sufficient convective heat transfer enhancement. Assess operating speeds when this heat transfer is achieved.

Sandia

Characterize refrigerant flow (Experimental)

Confirm that centrifugal/Coriolis forces indeed separate the liquid/vapor phases. Confirm that refrigerant flow axisymmetric.

Sandia + CTS

Assess manufacturability

Confirm that resistance projection welding is a viable method of merging two clam-shell structures.

Develop design for 1kW RVCC prototype

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 and standard shapes (i.e. cylinders, plates) as upper bound prediction
  - Compare to HTC for non-rotating flat plate with similar airflow velocity to assess HTC enhancement in rotating frame
- Characterize HTC via transient cool-down tests

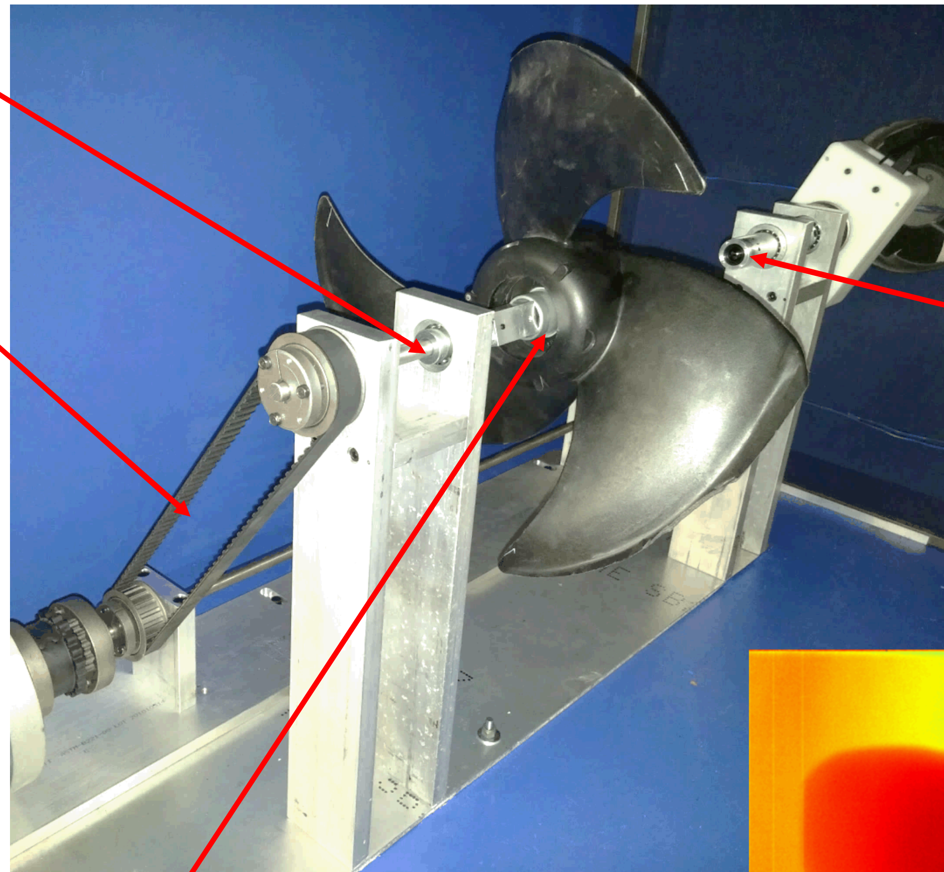
$$HTC = f(location\ on\ blade,\ RPM)$$

  - Determine HTC scaling characteristics with radius and RPM

Air-side Convective Heat Transfer Laboratory Setup

Fan and camera axially aligned

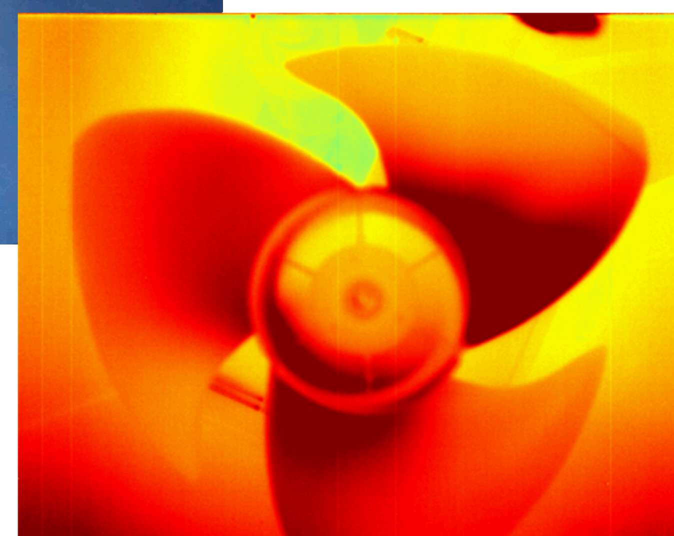
Fan and camera driven synchronously with timing belts



Infrared image acquisition system

Robust chuck allows quick replacement of fan blades

Infrared fan image



Co-rotating Infrared Imaging System

Flir Quark infrared camera

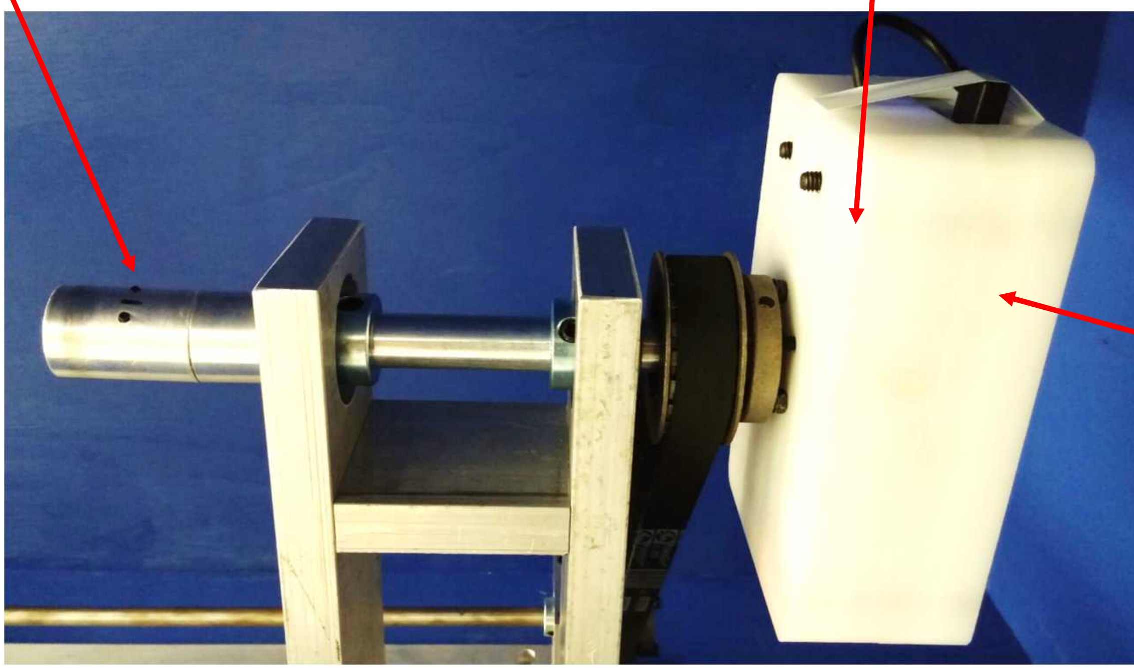
Small OEM core capable of withstanding high g-forces

640x512 pixel video with a temperature precision of 50 mK

Raspberry Pi 2

Triggers and saves IR images

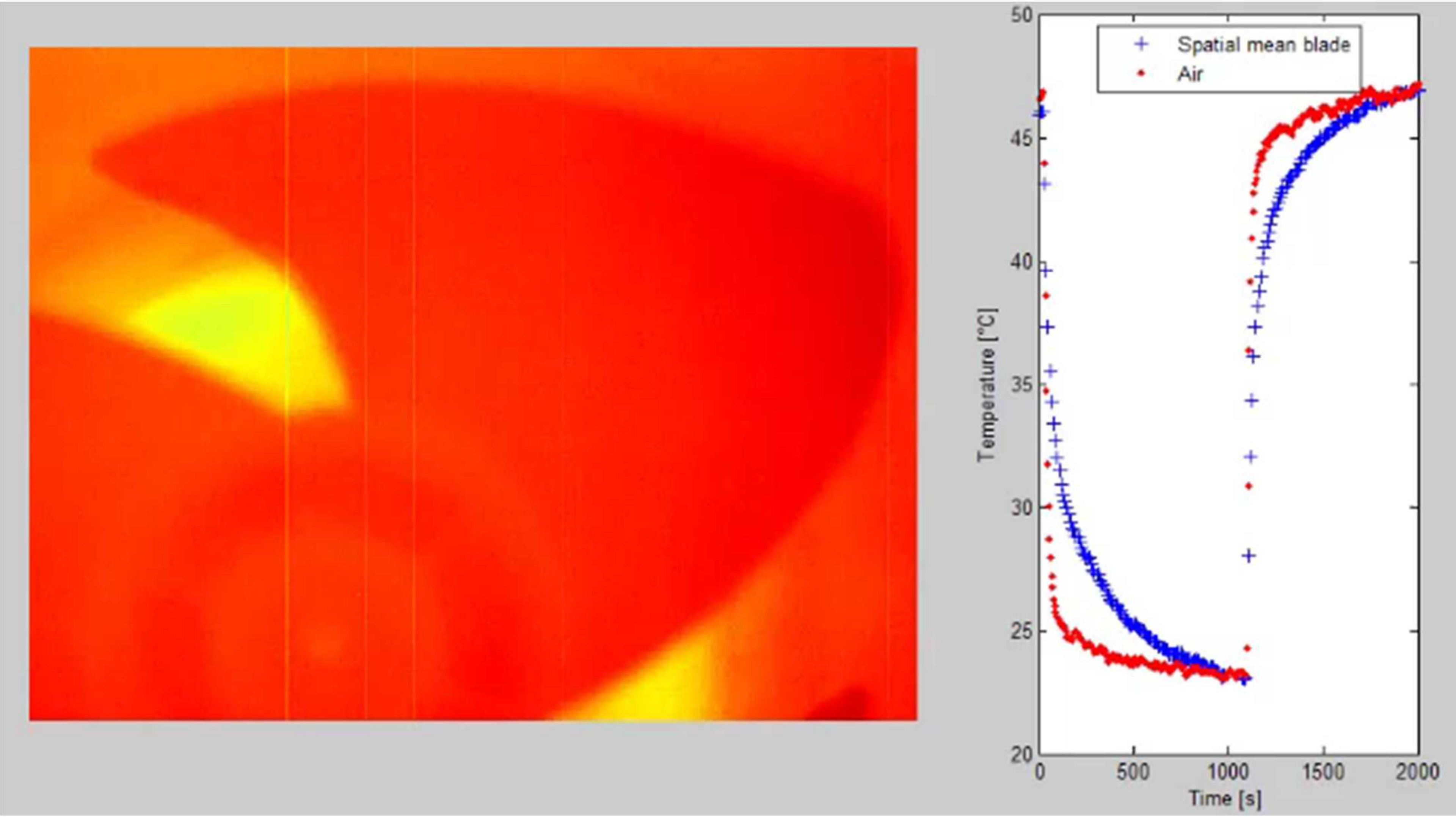
Transmits images via wifi for subsequent analysis



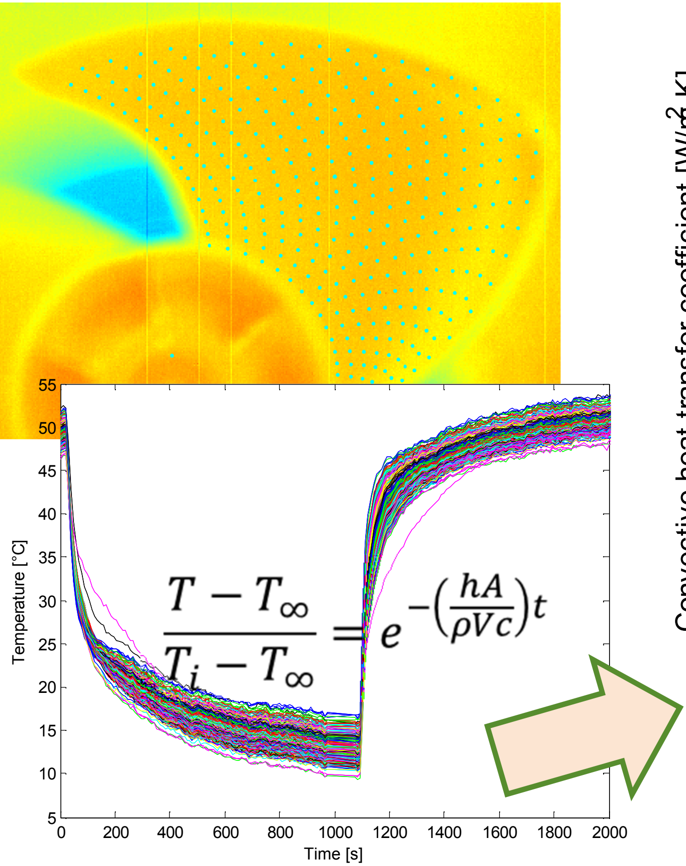
Battery

Delivers power to camera and computer without slip rings (2.0 Amps,10,000 mAh)

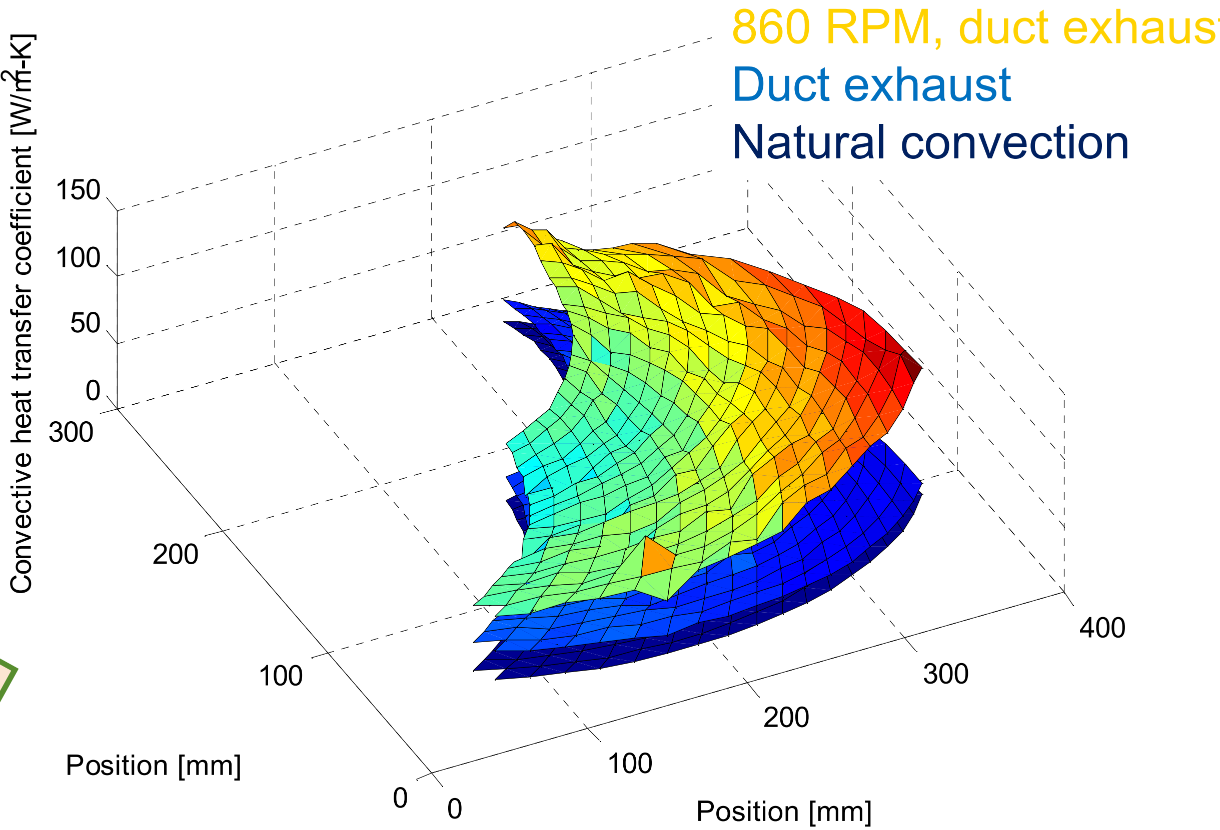
Overall Fan Blade Temperature



Heat Transfer Coefficient



$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\left(\frac{hA}{\rho V c}\right)t}$$



Method for determining convective heat transfer coefficient:

- Determine temperature at grid of points on fan blade
- Fit exponential decay function (determine time constant)
- Determine ratio of time constant to time constant with known heat transfer coefficient

Preliminary results show rotating blade gives about 20% higher convective heat transfer than would be expected with a flat plate!

CHARACTERIZATION OF REFRIGERANT FLOW

GOALS:

1) Confirm axisymmetric refrigerant flow

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

   - Film/annular condensation
   - Film/annular evaporation

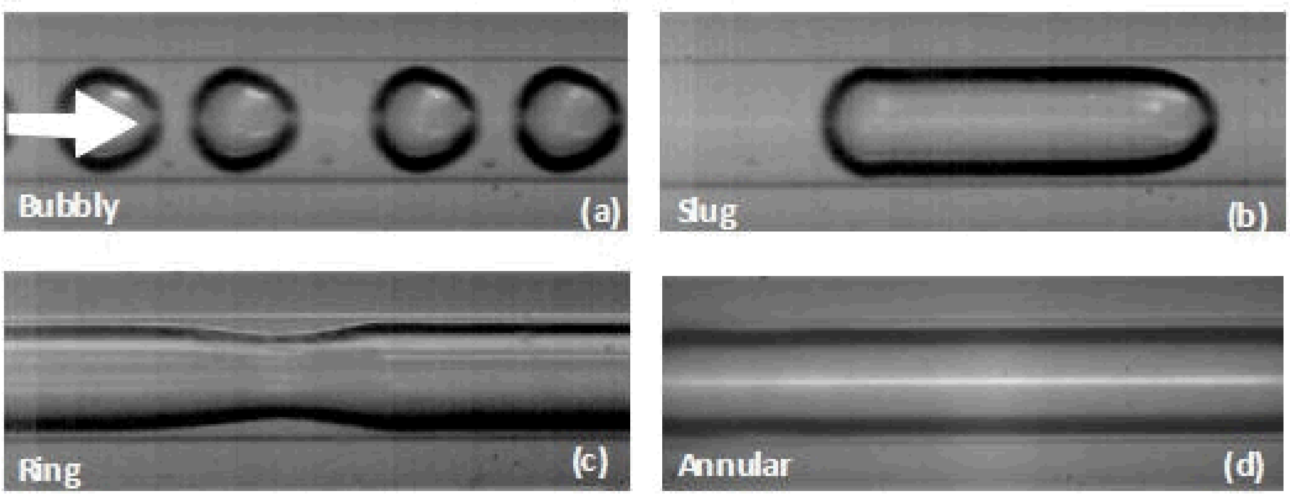
Methodology

- 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

Phase Change in the Rotating Frame

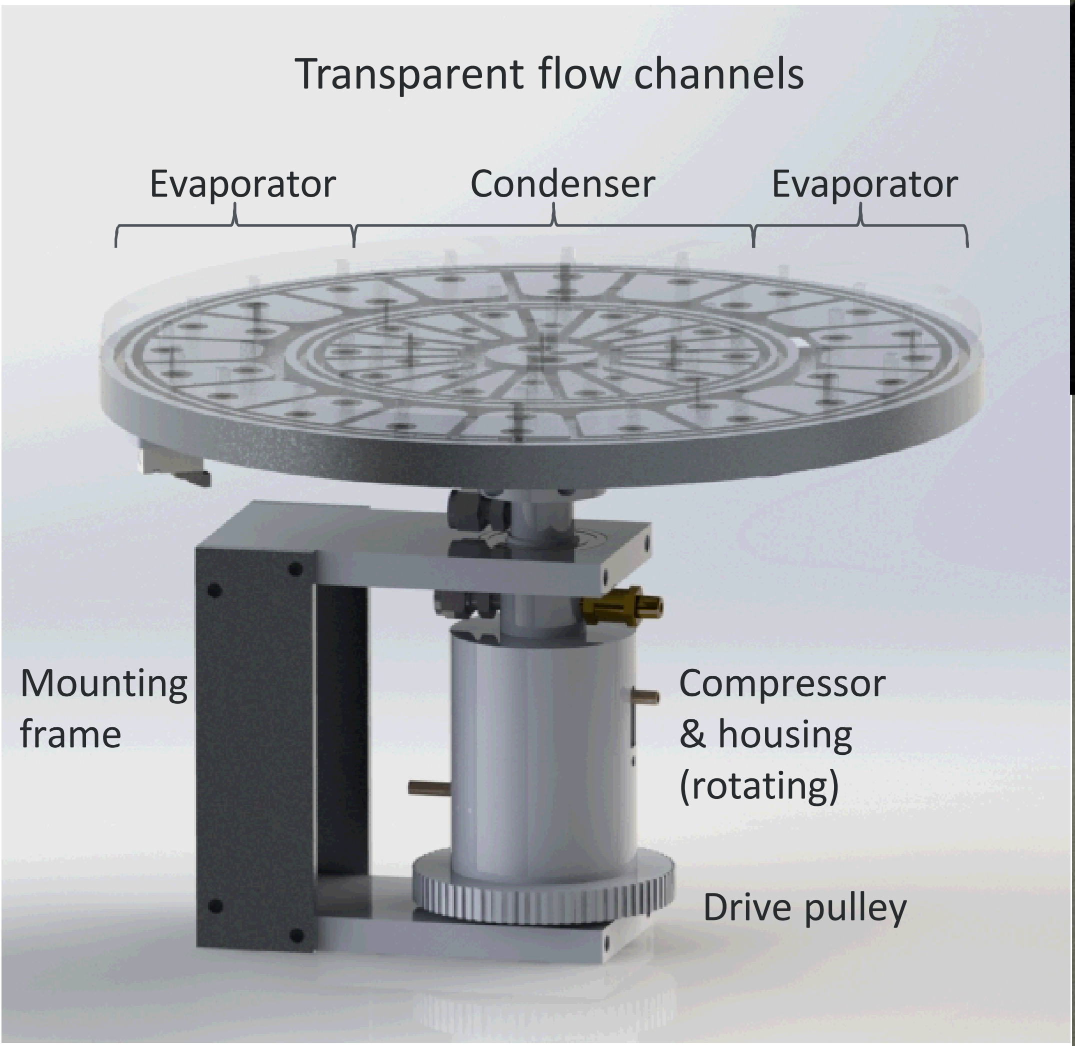
- Significant research has been directed at improving heat transfer in evaporating (condensing) channels flows
  - Problem 1: Access of liquid (vapor) to heat transfer area
  - Problem 2: Escape path of vapor (liquid) after phase change
- Potential improvements from centrifugal and Coriolis forces:
  1) Separation of phases due to density difference – allowing for easier access to heat transfer area and escape path after phase change
  2) Rapid transport of fluid to heat transfer surface

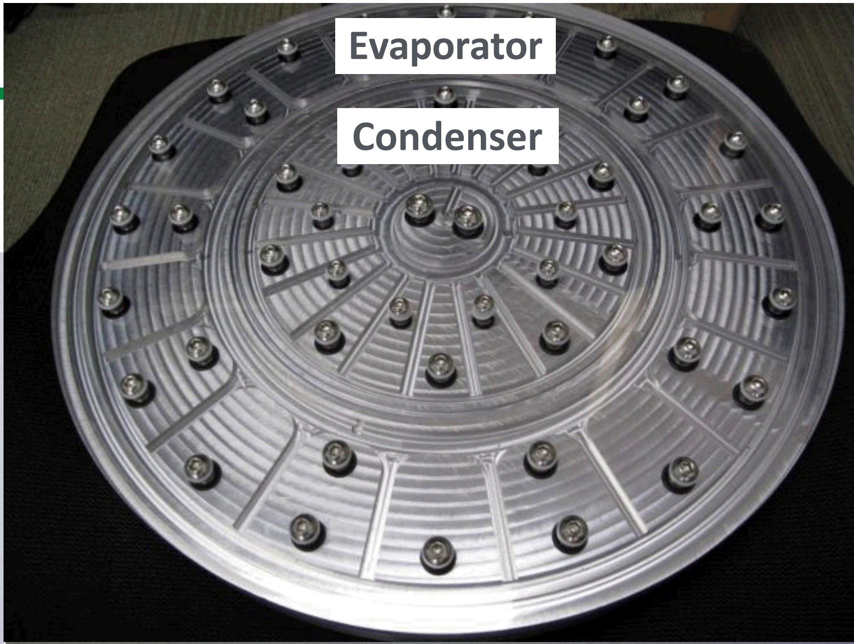
Flow regimes in non-rotating two phase flow[7]

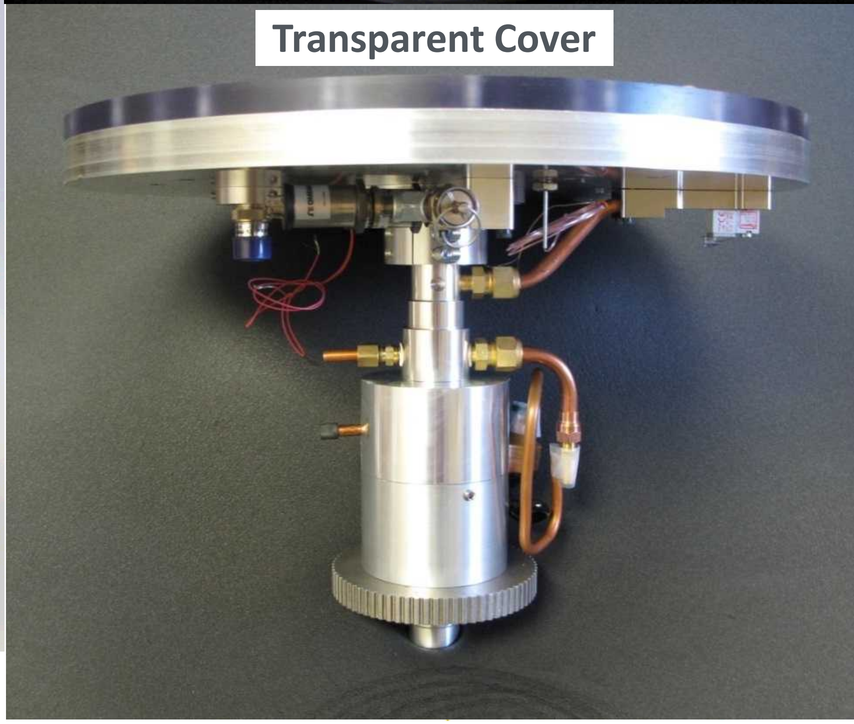


7. http://www2.egr.uh.edu/~dli9/research.htm

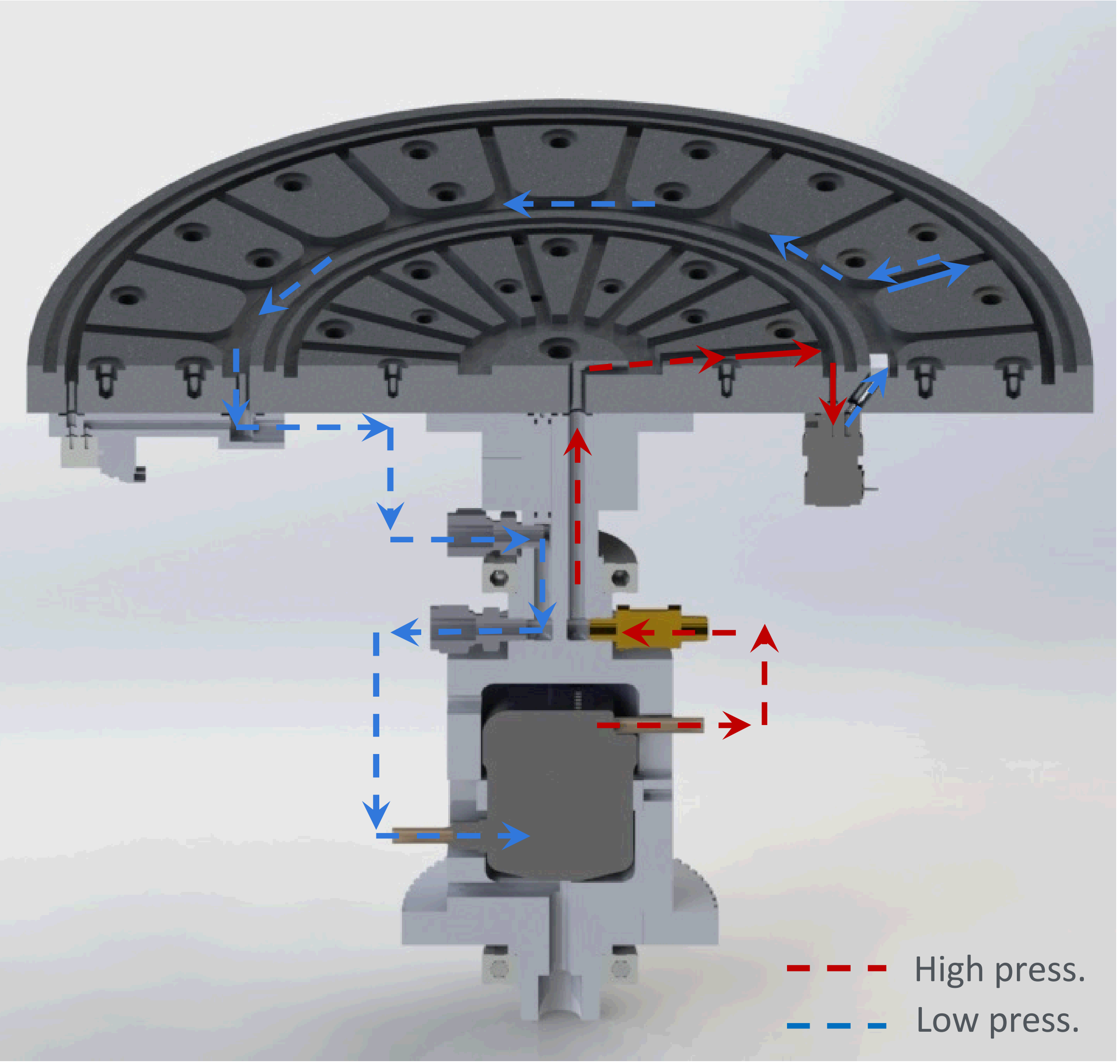
Refrigerant Visualization







Experimental Details



- Relevant experimental details:
  - Compressor: 1.9 cc/rev
  - Liquid refrigerant volume: 40-90 mL
  - System RPM: 0-600 RPM
  - Refrigerant: R134a
  - Camera resolution:
    - 4k HD @ 30 FPS
    - 1080p @ 120 FPS

- Experimental goals:
  - Demonstrate VCC in rotation
  - Visualize liquid distribution in evaporator and condenser (flooding)
  - Visualize symmetry of refrigerant flow
  - Analyze effect of throttle opening on liquid distribution
  - Analyze the effect of refrigerant filling volume
  - Analyze two-phase flow pathologies

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Progress and Accomplishments

Accomplishments:

1) Patent application filed: 4/857,652
2) A de-rotated imaging apparatus was developed for in-situ IR thermography of rotating heat transfer surfaces
3) A rotating VCC was developed for investigating phase change behavior in the rotating frame. This will be the first investigation of its kind.

Market Impact:

1) Efforts to ensure/accelerate impact: For actual commercial impact, economical manufacturability at high volume is critically important. Efforts will be made to develop a quick, highly parallelized manufacturing technique for fabricating the RVCC blades.

2) Quantitative performance gains: Experimental quantification currently in process.

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

Lessons Learned: NA

Project Integration and Collaboration

Collaborators: Creative Thermal Solutions is taking the lead on the air-side heat transfer studies. They have experimental facilities that are 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: A part of the work will be presented at the International Refrigeration and Air Conditioning Conference (July, 2016)

Next Steps and Future Plans

Year 1-3

Current BTO project and immediate follow-on (TRL 2 → 4)

- Confirm refrigerant/air flow benefits in rotating frame
- ***Proof-of-concept stage***
- ***Build/test scaled-down RVCC (1 kW)***

Year 4-5

Follow-on funding for design refinement and scaling up (TRL 4→5)

- Work with industry partner
- Develop feedback throttling control
- Further enhance refrigerant flow with internal structures and by altering surface wettability
- Implement economical manufacturing scheme on actual heat exchangers
- ***Build/test 10 kW RVCC***

Year 6

Transition/license technology to industry for commercialization

- Use 10 kW prototype to gather industry interest
- Similar transition path as used for the TRL 5 Sandia rotating heat sink

Image: http://www.njcti.com

Rooftop ACs are limited in efficiencies due to weight restrictions. The lightweight RVCC can break that barrier.

REFERENCE SLIDES

Project Budget

Project Budget: $774,000 DOE + $86,000 Cost share
Variances: Final report deadline extended to February
Cost to Date: $614,000 DOE + $64,000 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

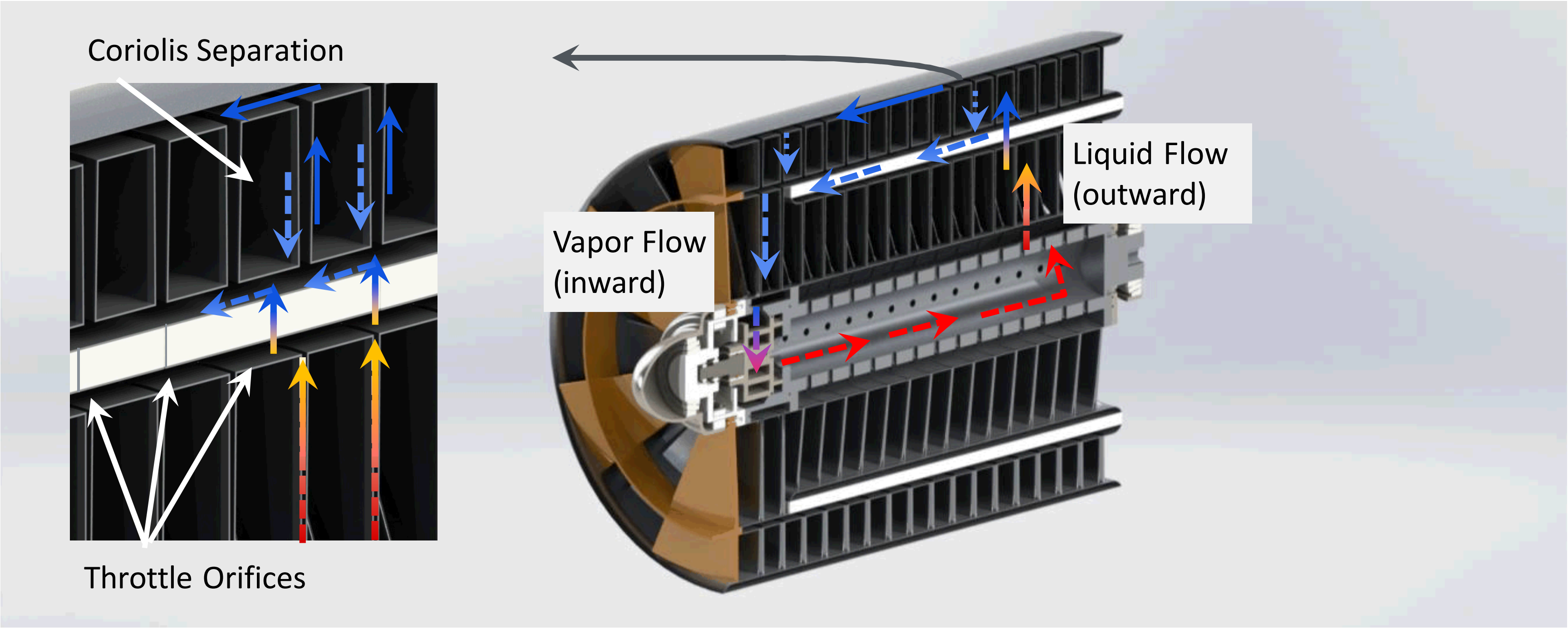
Project Plan and Schedule

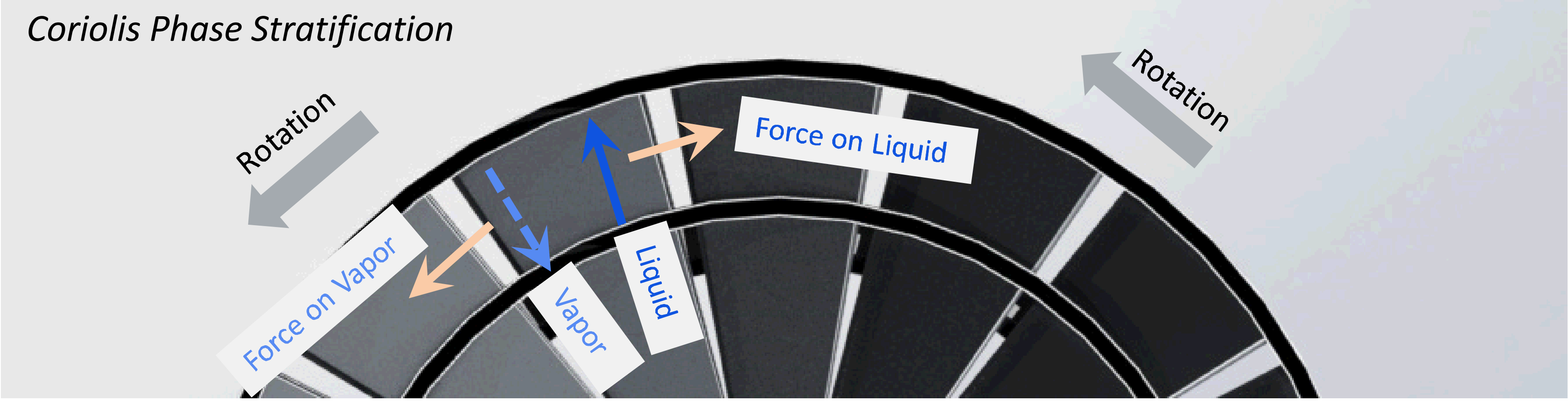
Project details

- Initiation: Sept. 2014 (FY15); End: Feb. 2017
- Ending date (submission of final report) was moved to Feb. 2017 with program manager approval
  - Final report will include design details of 1kW RVCC prototype, the development of which will be financially helped by Sandia internal funding
- Initial delays encountered in developing rotating imaging (IR, visible light) facilities; with those facilities in place, future experimental efforts expected to progress as scheduled
- Go/no-go decision points:
  - Is there sufficient air-side heat transfer enhancements and refrigerant-side flow benefits in the rotating frame? (May 2016)
  - Does the RVCC operate as expected? (Dec. 2016)
- Manufacturing assessment/cost estimate milestone was moved to later in the project in order to prioritize confirming the fundamental physics underlying the RVCC concept

Project Schedule												
Project Start: September 2014		Completed Work										
Projected End: February 2017		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	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 vizualization												
Current/Future Work												
Milestone: Manufacturing assessment / develop cost estimate												
Milestone: Fabricate and assemble prototype test components												
Milestone: Charge assembly with refrigerant												
Milestone: Test evaporator in frosting conditions												
Milestone: Write final report												

Details of Refrigerant Flow





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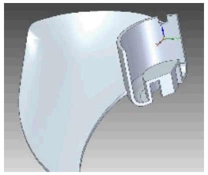
Finite Element Modeling to Calibrate Experiments

- Blade material: polyamide
  - Molar mass: 226.32 kg/kmol
  - Density: 1240 kg/m^3
  - Specific heat capacity: 1670 J/kg-K
  - Thermal conductivity: 0.25 W/m-K
- Blade initial temperature: 61 ^oC
- Ambient air temperature: 21 ^oC
- Boundary heat transfer coefficient: 8 W/m^2-K
- Total time: 70s



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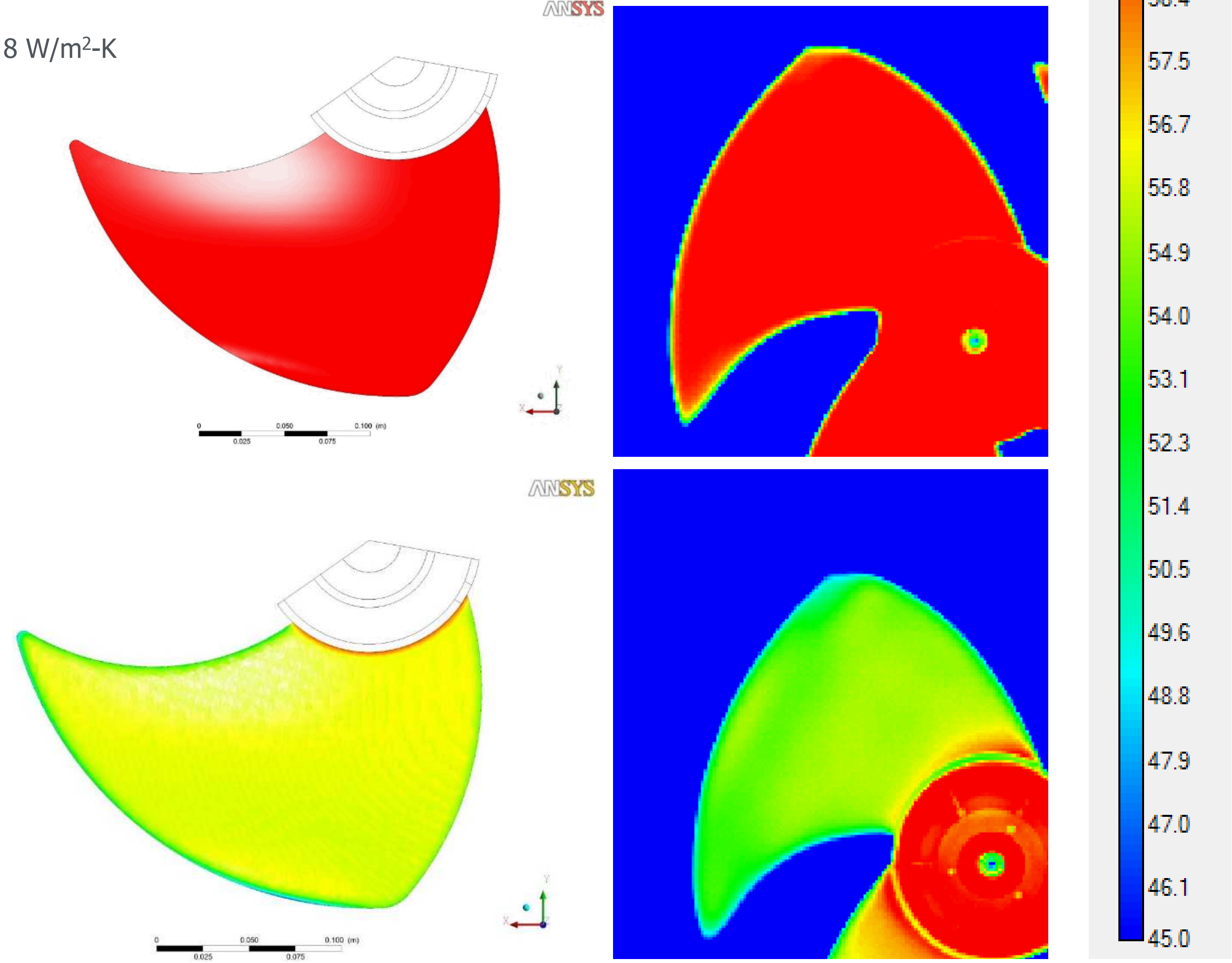
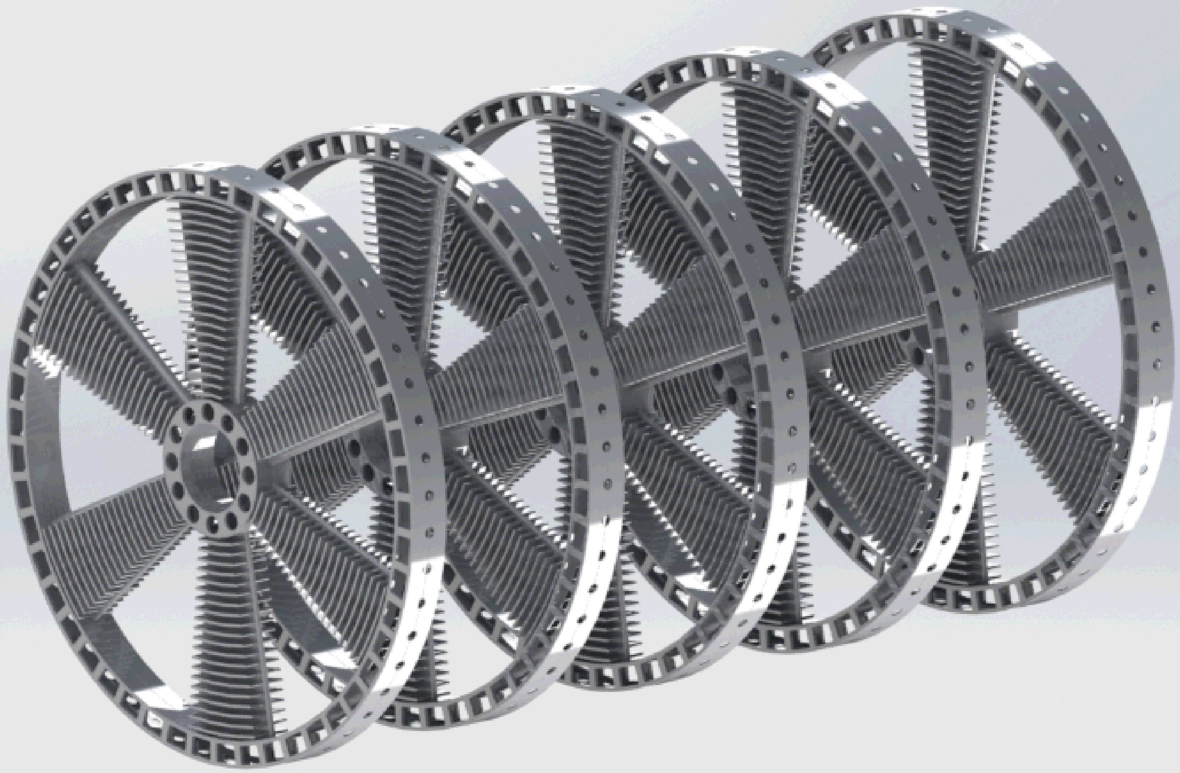
T=120 seconds



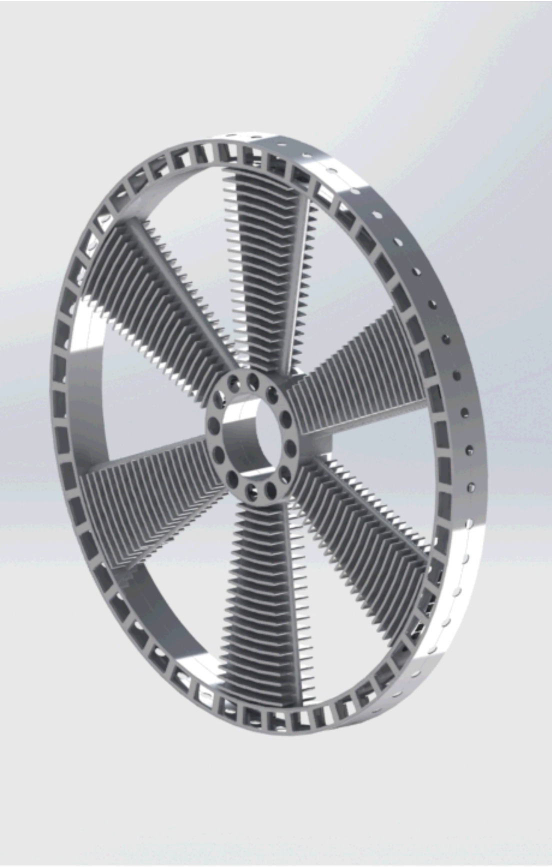
Manufacturing



Proposed fabrication:

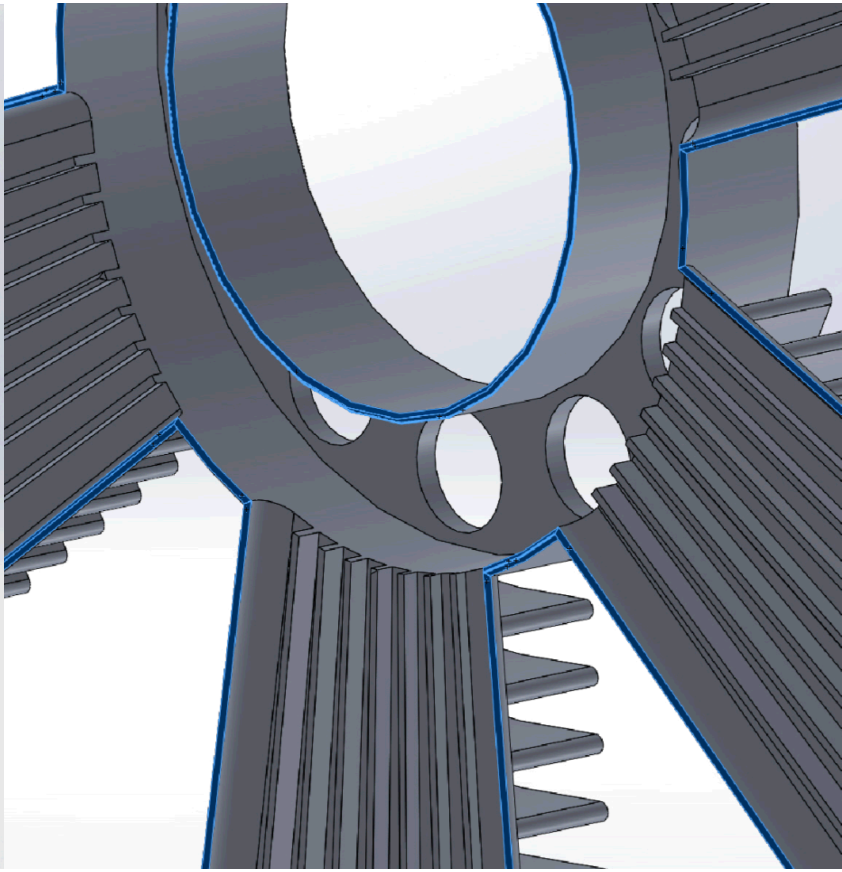
1) Cold forge parts
2) Resistance projection weld the stack of forged parts

Manufacturing



Single "layer"

Single "shell"



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