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SAND2013-10014P

Sandia National Laboratories

Sandia Cooler Program Overview

Terry Johnson, DMTS

Presented to Whirlpool

November 19, 2013

U.S. DEPARTMENT OF ENERGY

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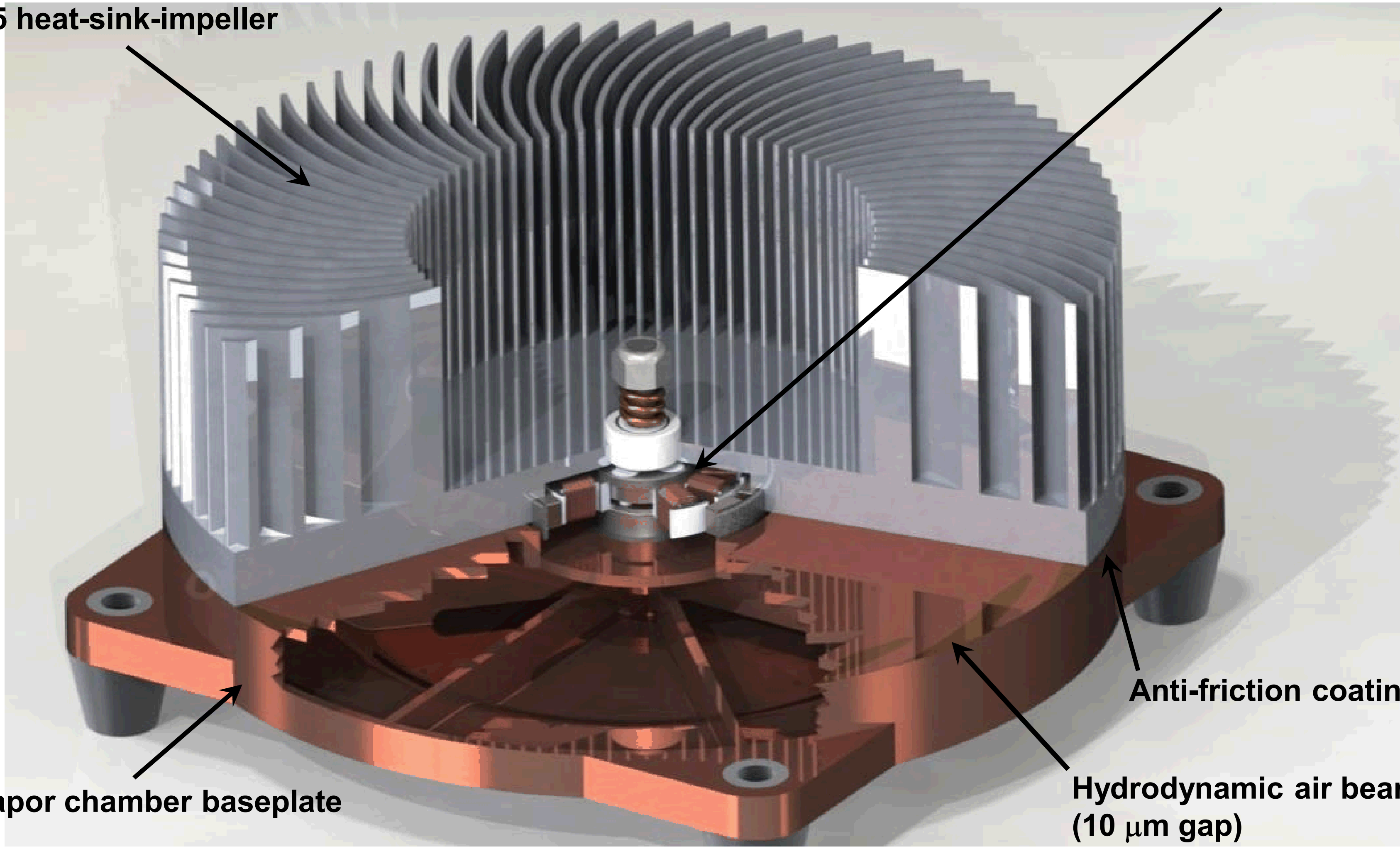
NNSA National Nuclear Security Administration

Latest CPU cooler design represents the culmination of several years of development



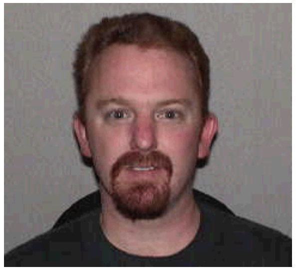
V5 objective: fully matured radial air bearing heat exchanger technology, tech transfer ready

V5 performance goals: R = 0.1 C/W at 3000 rpm, very low noise, 5 W power consumption

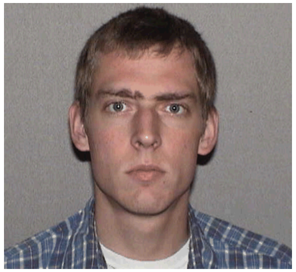
The team includes 14 scientists, engineers and technologists

Terry Johnson
MSME: Radial flow project lead and system engineer

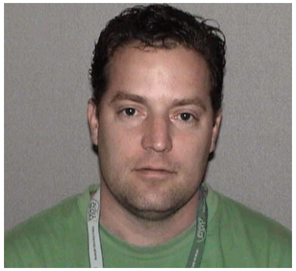
Imane Khalil
PhD ME: Project Manager



Mark Zimmerman
BSEE: Motor control development



Mike Leick
MSME: Motor control and anti-friction coatings



Jeff Koplow
PhD Chem: Inventor, technical advisor, axial flow R&D lead

Ryan Gorman
EE: Motor control development

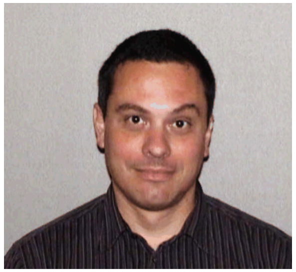
Nathan Spencer
MSME: Structural dynamics

Justin Vanness
MSME: Motor control development

Wayne Staats
PhD ME: CFD for radial and axial flow impeller design

Kent Smith
Mech. Tech.: Fabrication and mechanical design

Patricia Gharaghozloo
PhD ME: CFD/Heat Transfer



Marco Arienti
PhD ME: CFD/Heat Transfer

Daniel Matthew
BSME: Impeller fabrication and mechanical design

Ethan Hecht
PhD ChE: Impeller performance characterization

Arthur Kariya
PhD ME: Heat pipe design

Test stands have been developed to evaluate all aspects of the Sandia Cooler

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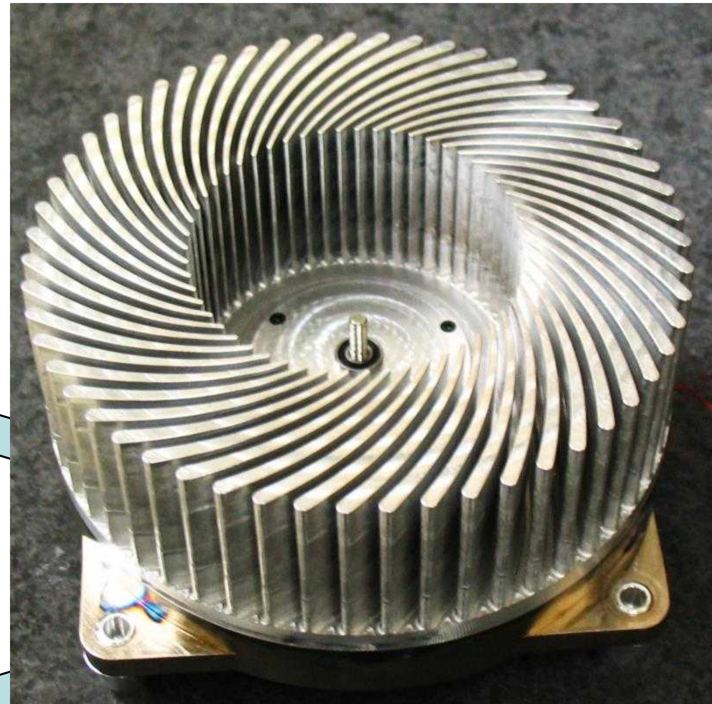
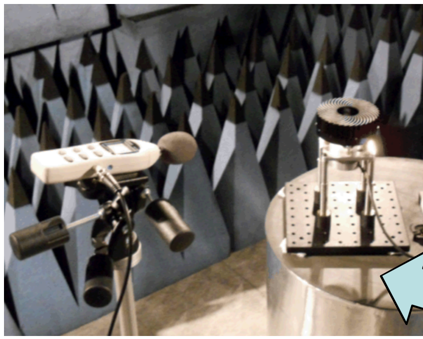
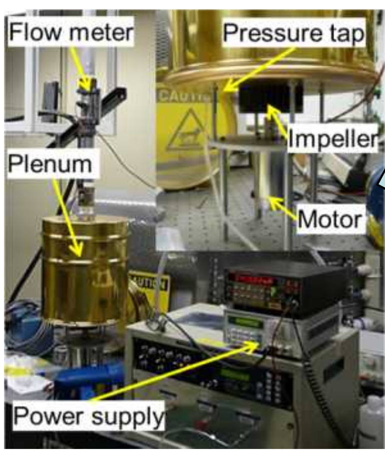


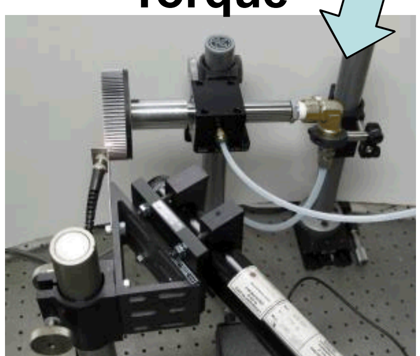
Acoustic



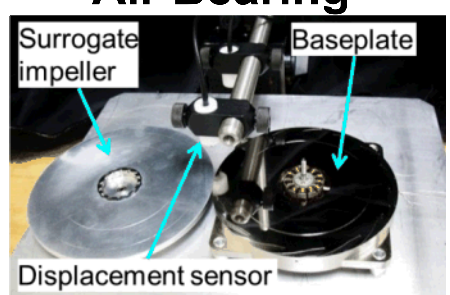
Pressure-Flow



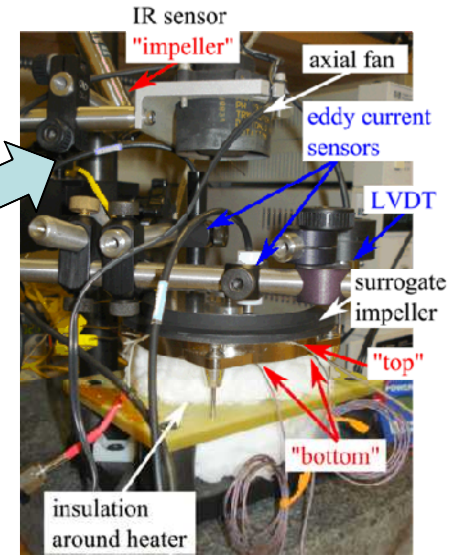
Torque

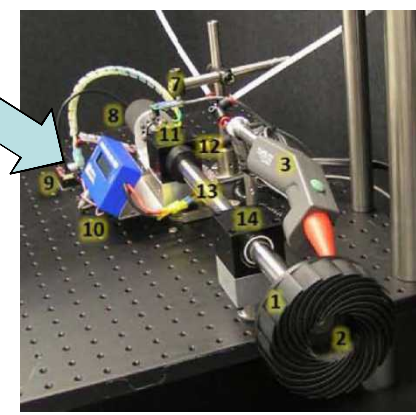


Air Bearing



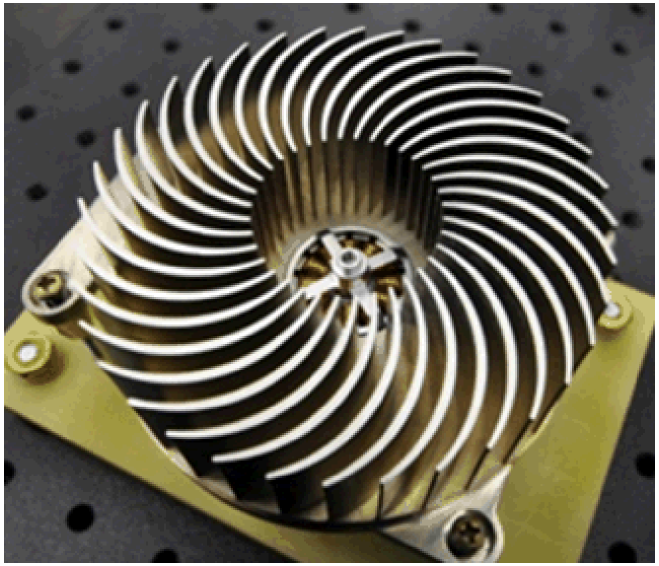
Thermal Resistance





Three different impeller geometries have been extensively characterized

V4



OD	4.0”
ID	1.5”
Fin Height	1.0”
# Fins	36
Shape	Intersecting arcs

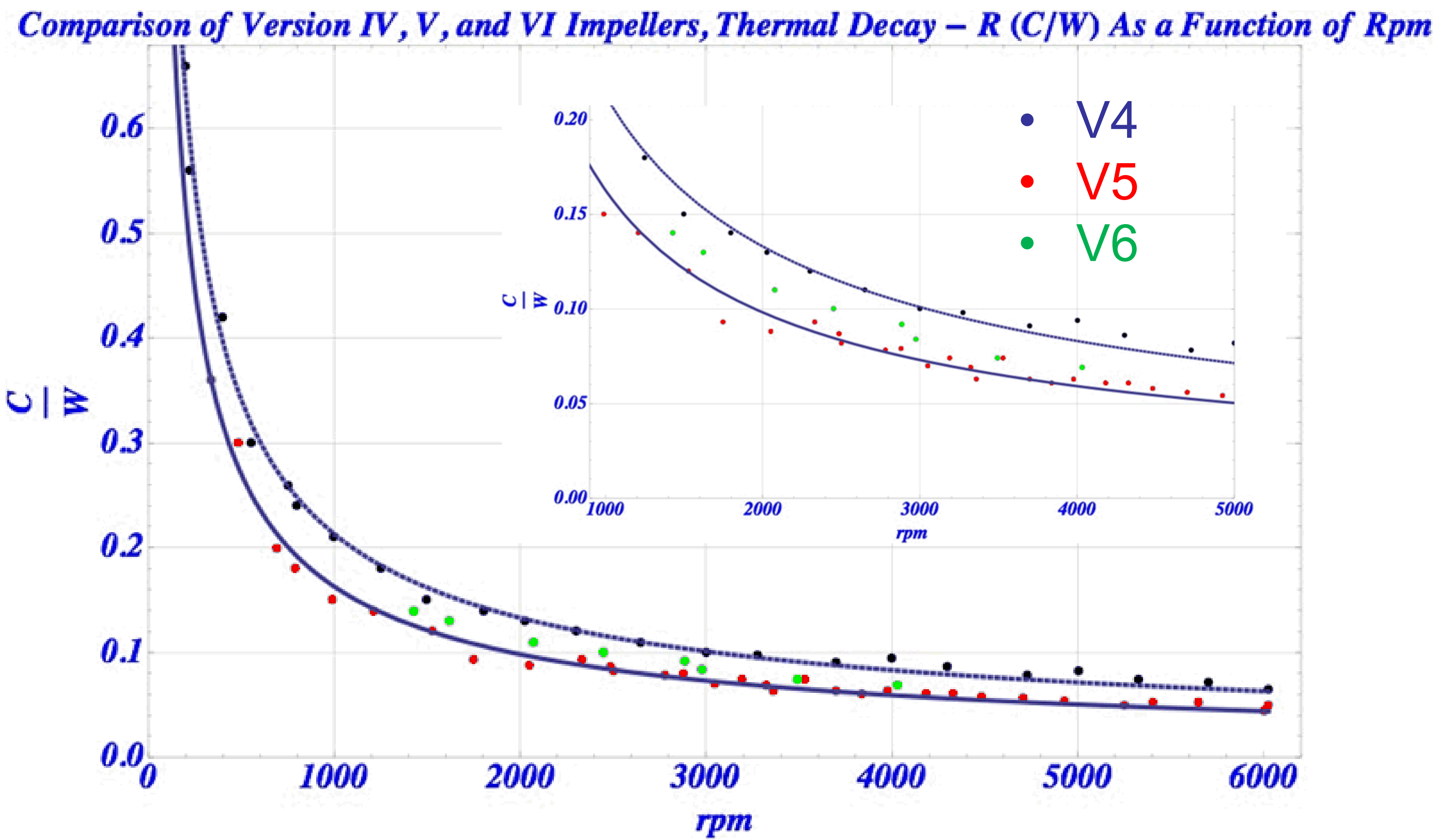
V5

OD	4.0”
ID	2.0”
Fin Height	0.95”
# Fins	80
Shape	Arcs

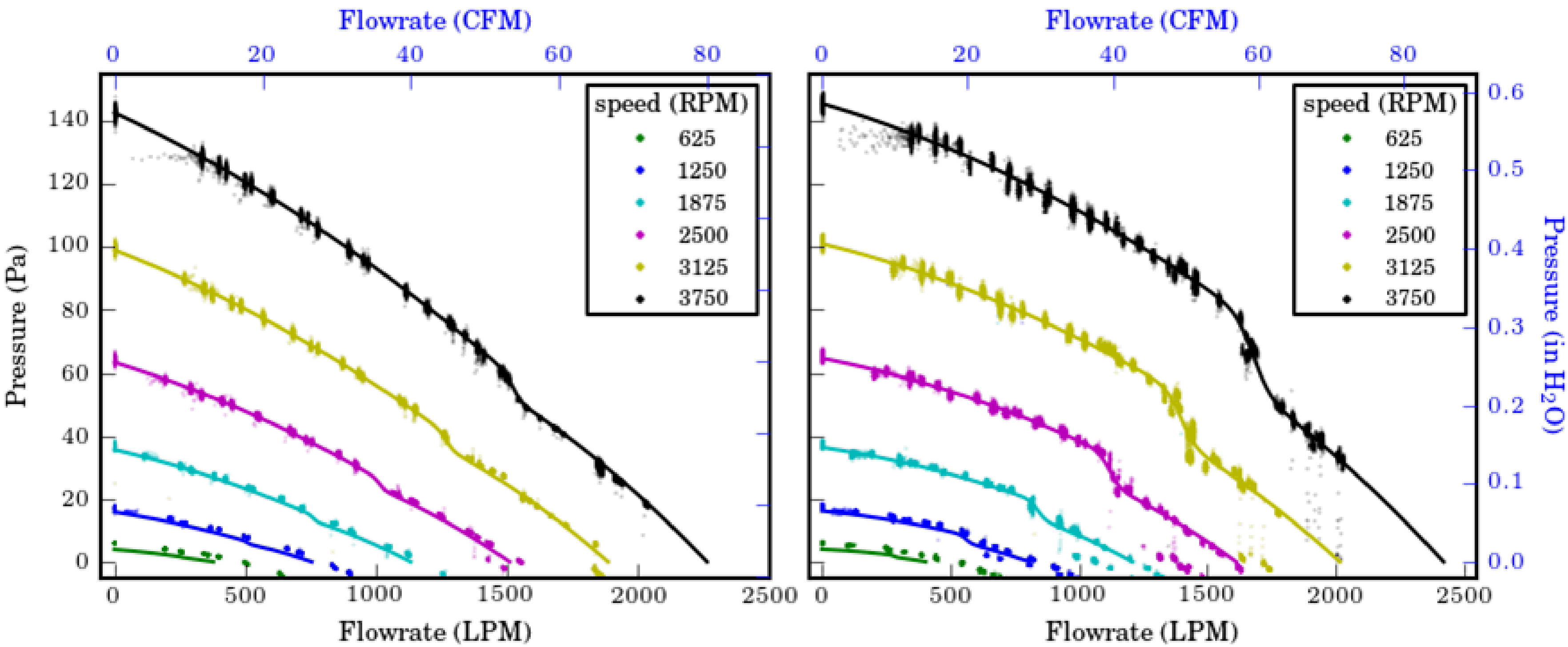
V6

OD	4”
ID	2.0”
Fin Height	1.18”
# Fins	55
Shape	Log spiral

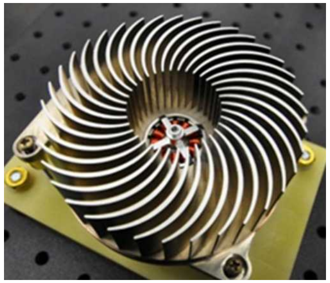
V5 impeller has the lowest thermal resistance tested



Pressure-flow curves were measured for several 4" impellers; V5 performed best

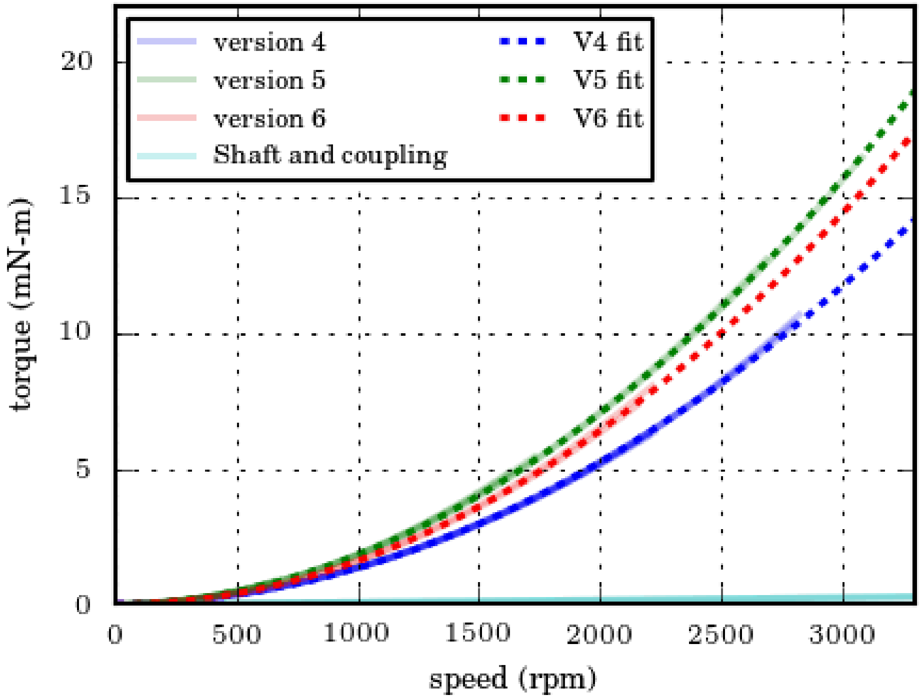


V4



V5

Impeller torque measured vs. speed; power consumption includes impeller and air gap torque



- Impeller power:

$$P = \tau \times \omega$$

@2500 rpm V5 P = 3W

Air gap power:

$$P = \tau \times \omega$$

$$\tau = \frac{\pi * \mu * \omega \left({r_o}^4 - {r_i}^4\right)}{2 * h}$$

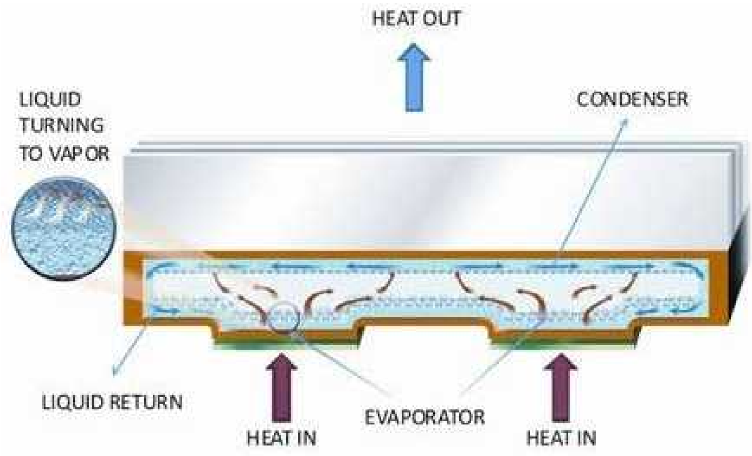
For a 10 micron air gap P = 1.3W

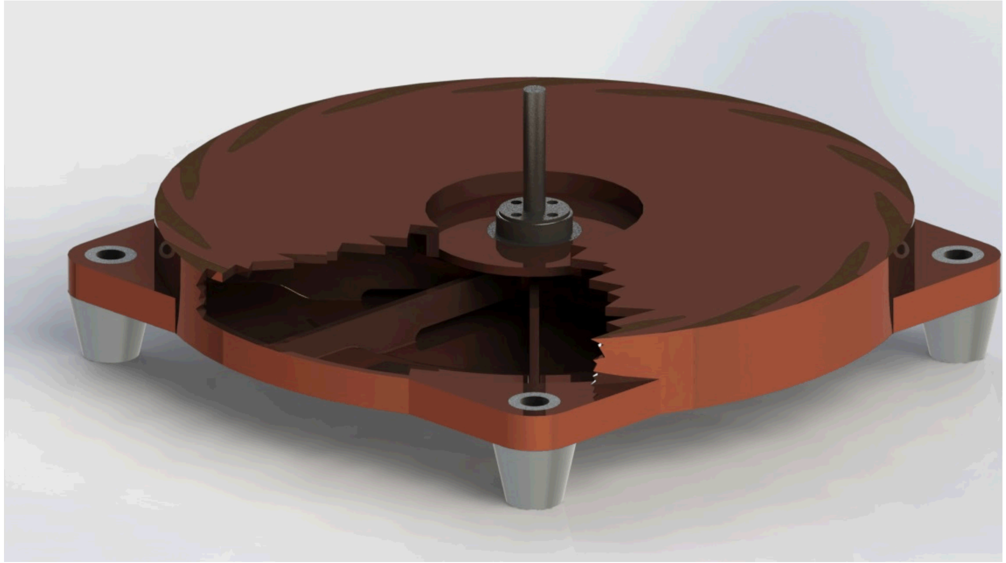
Total power:

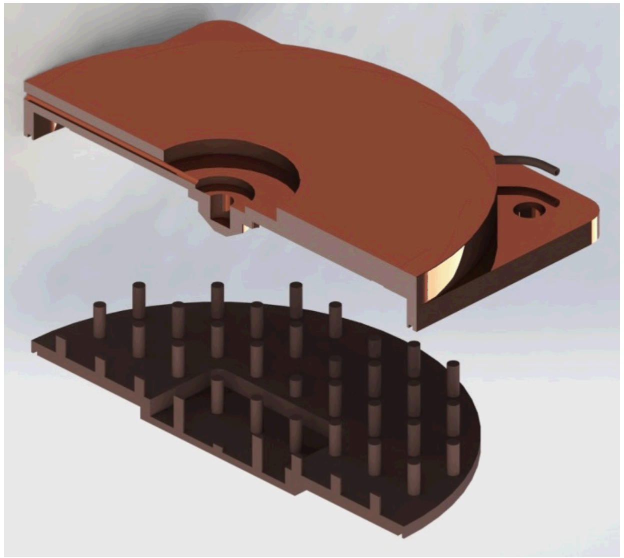
P_{mech} = 3W+1.3W = **4.3W**

Baseplate: Vapor Chamber Incorporation

- Spreading resistance of solid baseplate was unacceptably high
- Vapor chamber solution from Thermacore



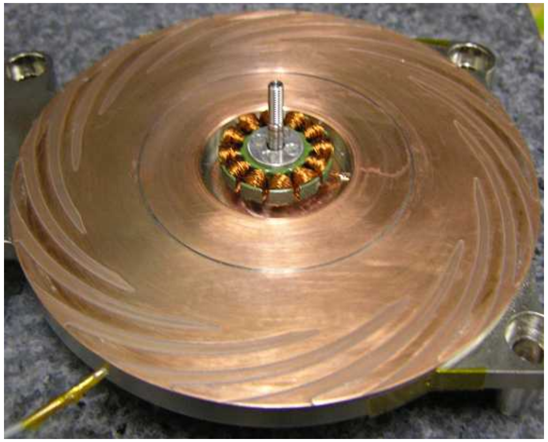




Air bearing design was improved through experiment and analysis

Original Design

Greater lift than needed
Significant pre-load for 10 μm gap
Groove area and depth larger than required



Parameters	
Ø_Impeller	101.6 mm
Groove Depth	81 μm
λ, r_Inner/r_Outer	0.75
α, Groove Angle	15°
k, # of Grooves	15
g, ridge width/groove width	1.0

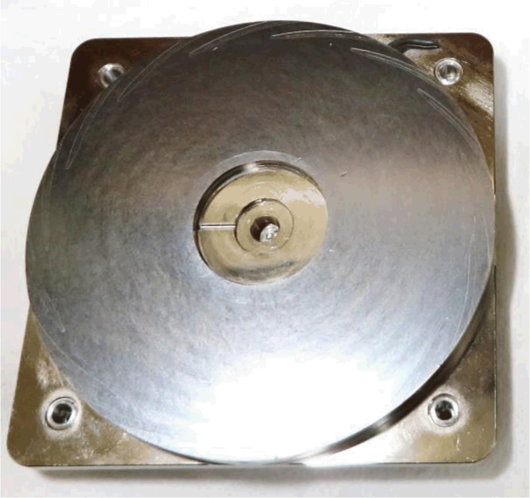
V5 Design

Good stiffness with less thermal resistance
Less sensitivity to impeller speed
Groove area still larger than required

Parameters	
Ø_Impeller	101.6 mm
Groove Depth	25 μm
λ, r_Inner/r_Outer	0.9
α, Groove Angle	15°
k, # of Grooves	15
g, ridge width/groove width	1.0

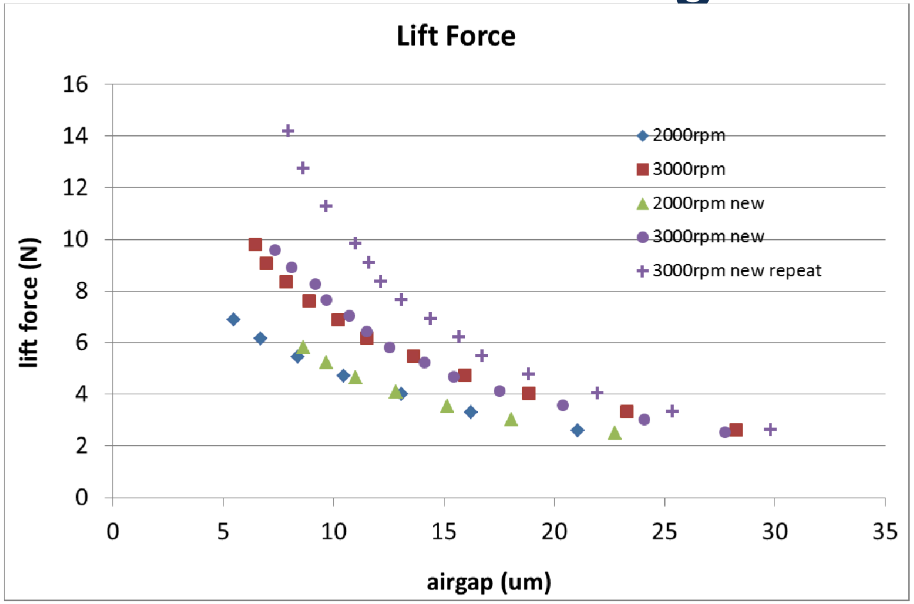
Final Design

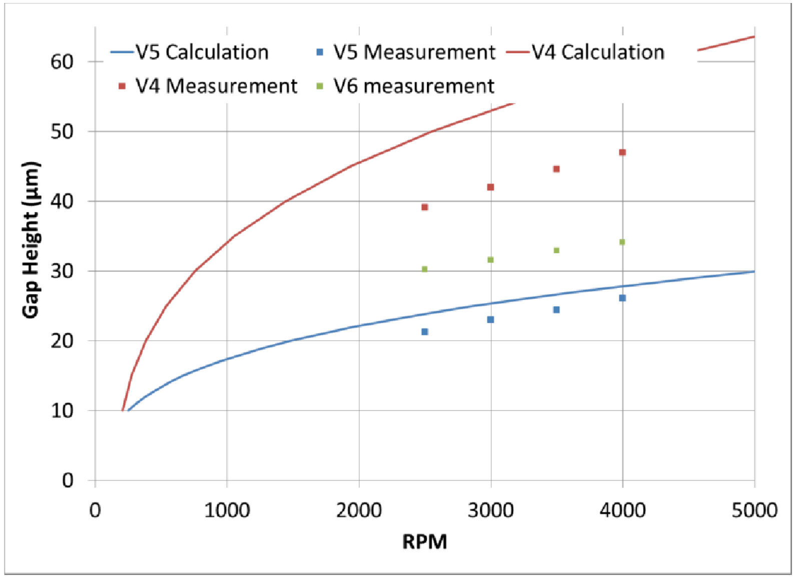
Maximum stiffness at a 10 μm gap
Minimal pre-load
Minimum thermal resistance

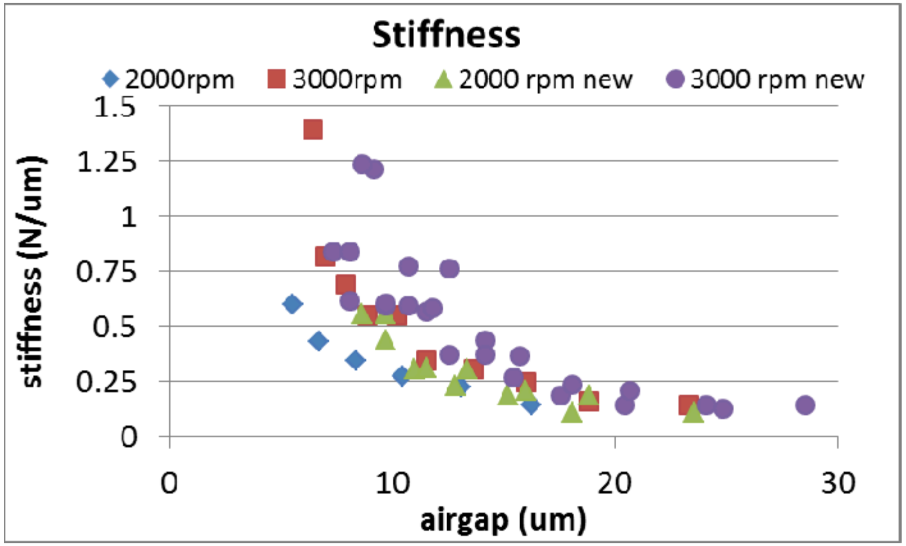


Parameters	
Ø_Impeller	101.6 mm
Groove Depth	35 μm
λ, r_Inner/r_Outer	0.9
α, Groove Angle	12°
k, # of Grooves	15
g, ridge width/groove width	1.4

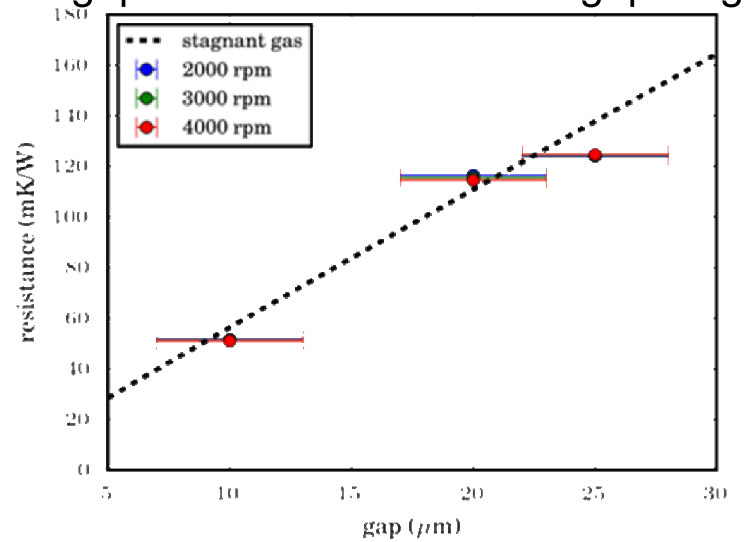
Air bearing provides stiff, low friction interface but thermal resistance is significant







Air gap thermal resistance vs. gap height



Two anti-friction coatings perform well out to 15,000 start/stop cycles

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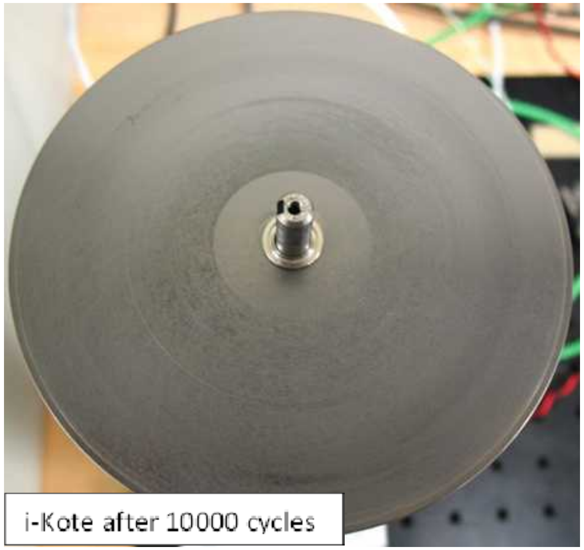
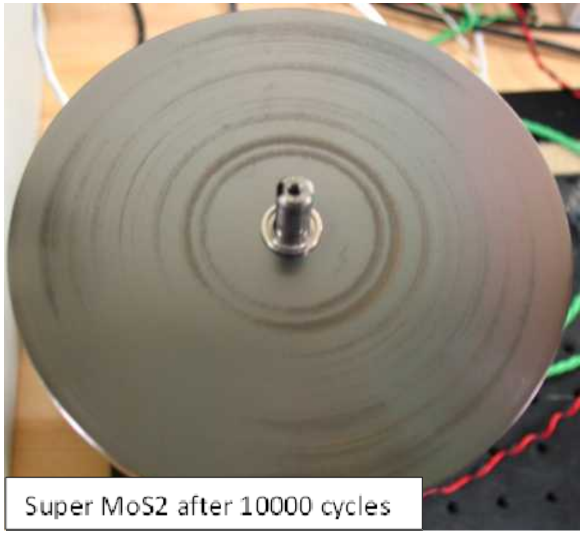
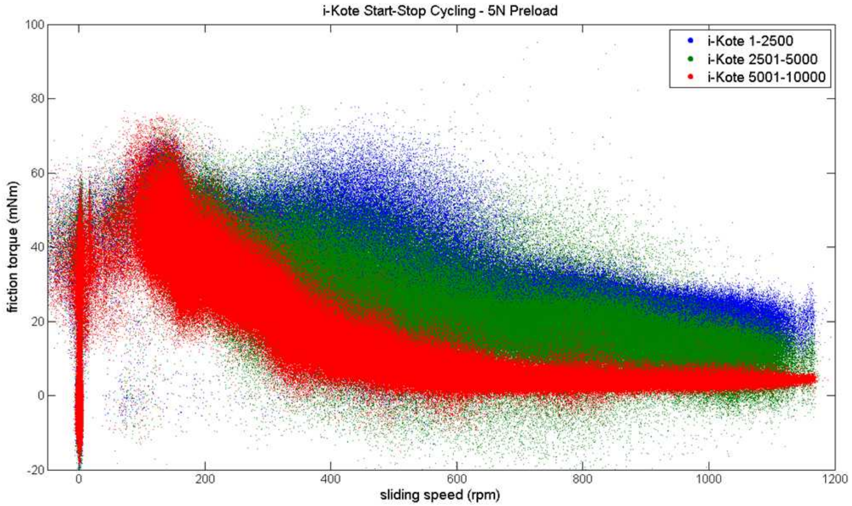
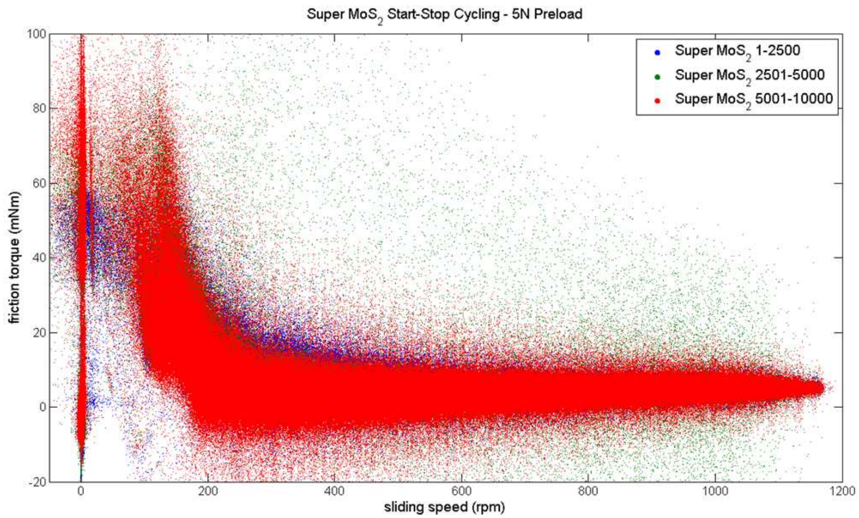


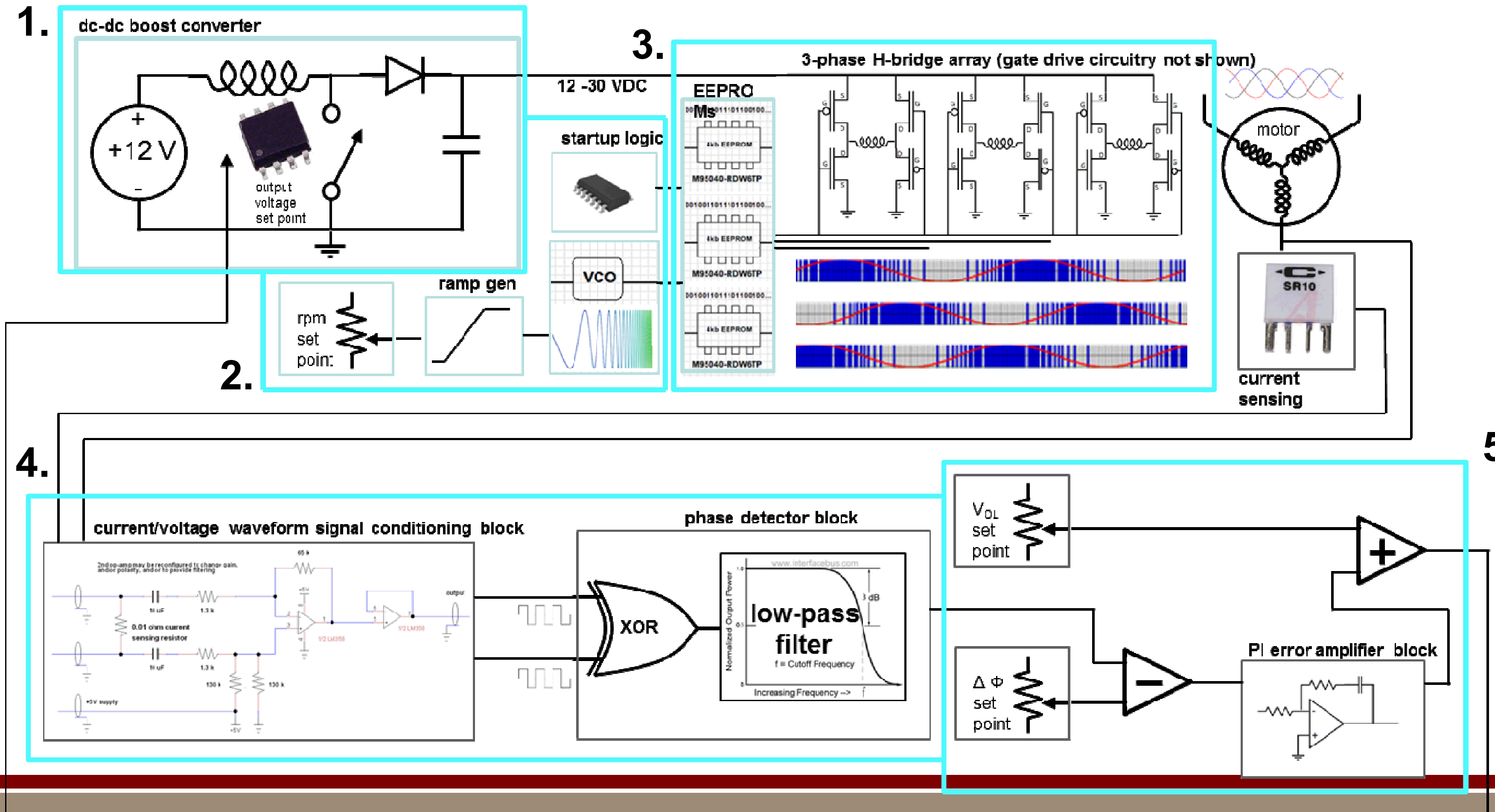






Custom motor controller in final stages of development

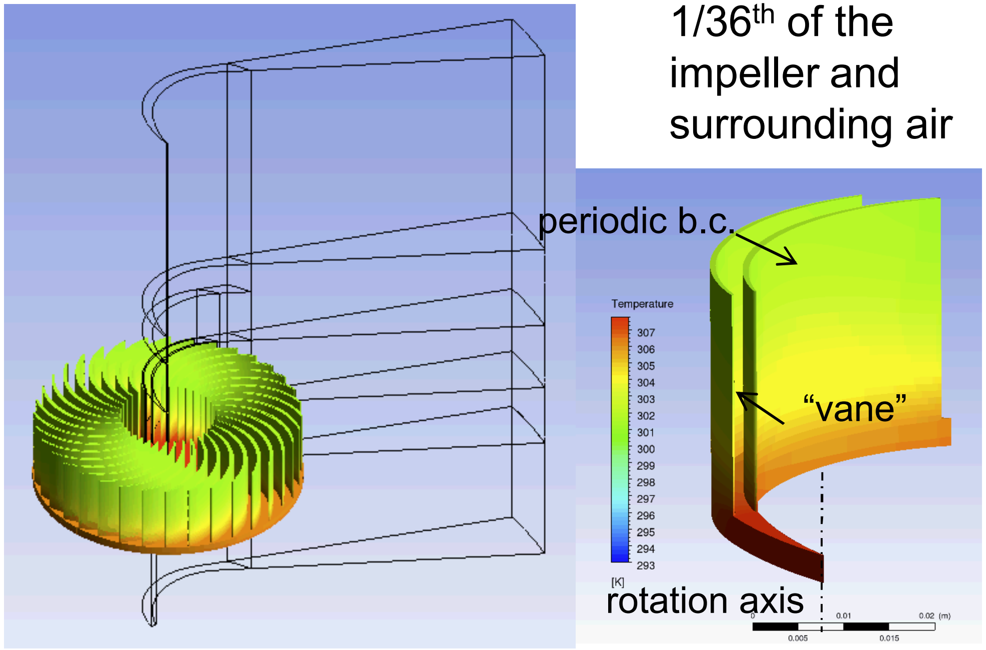
Five primary blocks: 1. Boost converter – prototyping complete, 2. VCO – final tuning for dynamic range complete, 3. H-Bridge – final tuning for efficiency and min heat loss complete, 4. Phase Detect – prototyping complete, 5. PI Loop – ongoing development



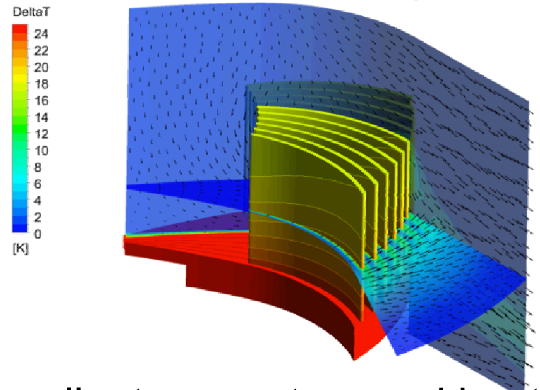
MODELING AND ANALYSIS

Computational fluid dynamics (CFD) models tell us a lot about the cooler performance

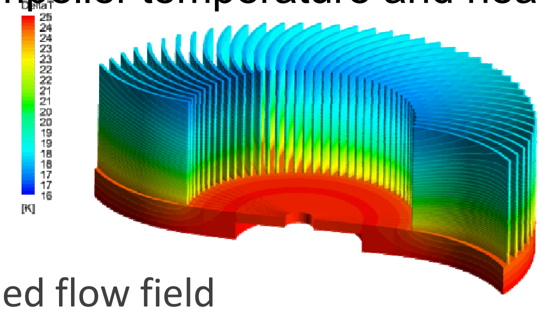
Example: V4 with 36 blades



Flow field and air temperature



Impeller temperature and heat flux



- ANSYS CFX V14.0
- Conjugate heat transfer (solid and fluid computation)
- Rotational reference frame for impeller
- Periodic boundary conditions take advantage of symmetry
- Reynolds-Averaged Navier Stokes (RANS) equations for flow field
  - Shear Stress Transport model

- Detailed flow field
- Temperature distribution in air
- Torque and power consumption
- Heat transfer coefficient
- Temperature distribution within solid regions
- Fin efficiency
- Where solid material is efficiently being used

CFD models have been experimentally validated

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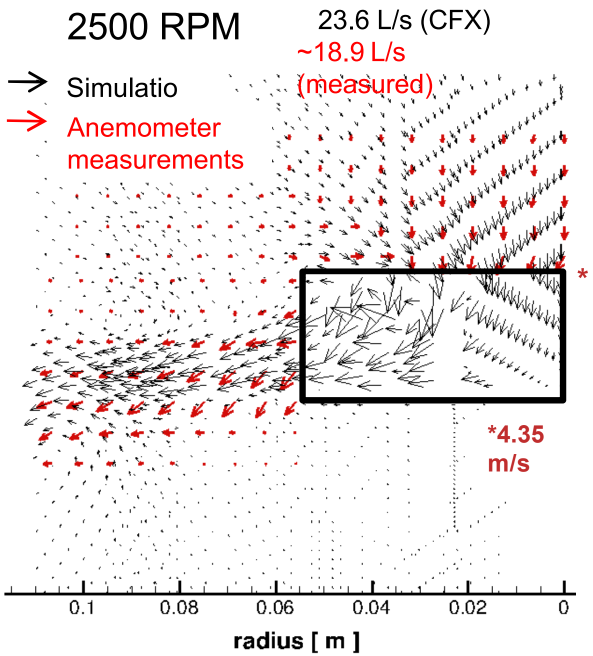
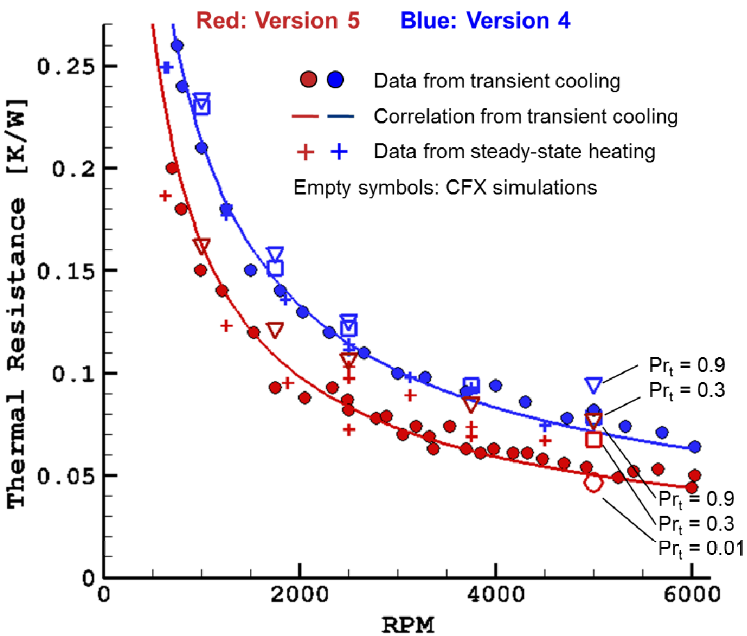
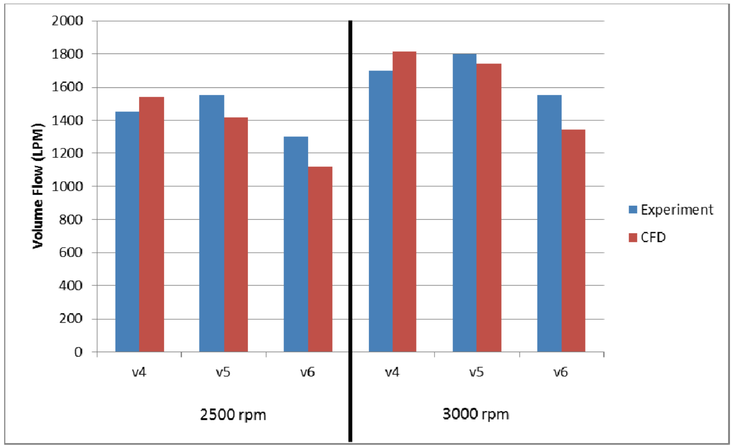
Flow Field



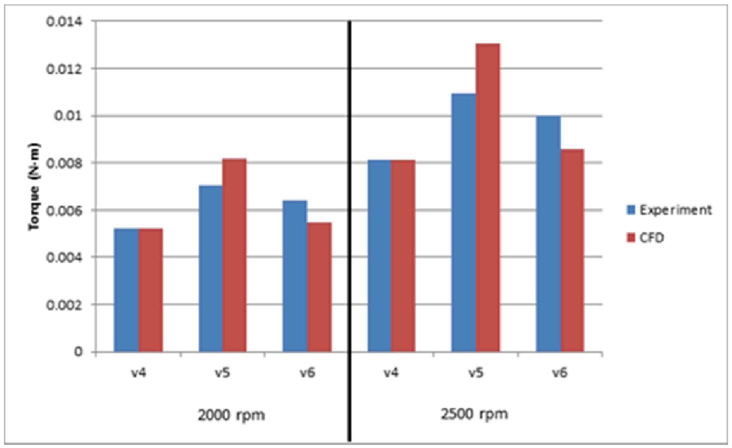
Thermal Resistance



Free delivery rates



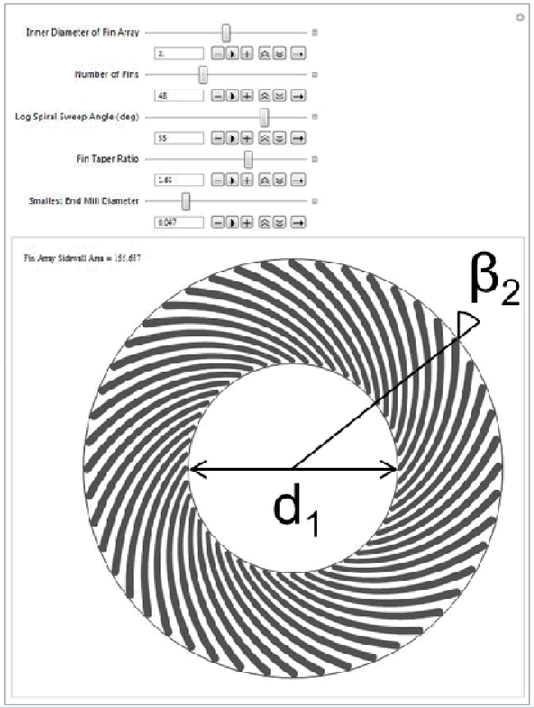
Torque (power) required to rotate impellers



CFD and design models have been used to carry out impeller parameter and scaling studies

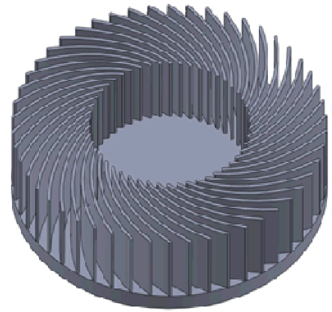
1. Generate Equations

Preliminary information (e.g. surface area) determined from Mathematica model



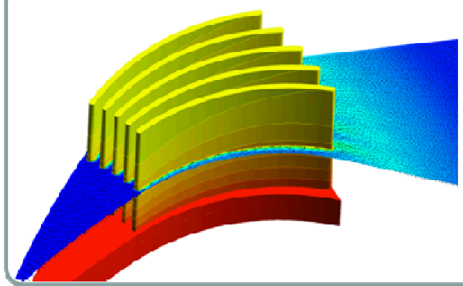
1. Inner diameter (d_1)
2. Blade angle (β)
3. Number of fins (n)
4. Minimum endmill diameter (d_e)
5. Fin Taper Rate (power law dependence of blade width on radius)

2. Create Geometry



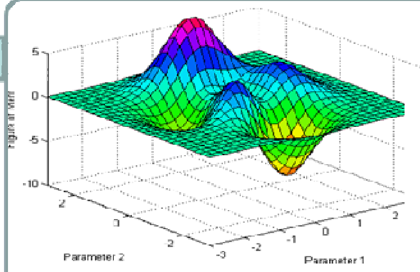
3D geometry generated from vector equations in SolidWorks

3. Simulate



Flow field and conjugate heat transfer simulated in ANSYS CFX

4. Evaluate



Determine sensitivity of thermal resistance to input parameters

Initial scaling study shows thermal resistance vs. motor power tradeoffs

CFD results for scale-up of V6 impeller

Height (cm)	Diameter (cm)	Speed (rpm)	R (K/W)	Torque (J)	Mass Flow (kg/s)	Power (W)
3	10	2500	0.097	0.0092	0.026	2.4
3	10	2500	0.118	0.0085	0.023	2.2
1.5	15	1666	0.119	0.012	0.021	2.1
1.5	15	2500	0.082	0.028	0.034	7.4
1.5	15	3000	0.071	0.041	0.041	12.9
1.5	15	5000	0.047	0.099	0.087	52.0
3	15	1666	0.079	0.021	0.038	3.7
3	15	1666	0.082	0.022	0.039	3.8
3	15	2500	0.061	0.050	0.061	13.0
3	15	2500	0.058	0.054	0.060	14.1
3	15	3000	0.054	0.073	0.074	22.8
3	15	5000	0.030	0.223	0.13	117.0
4.5	15	1666	0.051	0.033	0.059	5.7
3	20	1250	0.053	0.038	0.061	5.0
3	20	2500	0.030	0.143	0.15	37.5
4.5	20	2500	0.028	0.243	0.17	63.5
6	20	1250	0.031	0.079	0.11	10.4
6	20	2500	0.022	0.331	0.23	86.6
6	20	5000	0.017	1.353	0.48	708.5

- V6 geometry: 55 fins, 45°, 1” inner radius, 3 cm height, 1.5 power law
- Uniform in-plane scaling; 1.5X and 2X
- Independent vertical scaling for some cases; 0.5X, 1X, 1.5X, and 2X
- Speed scaled inversely with diameter based on V6 @2500rpm for some cases

BACKUP

Vapor chamber baseplate improvement over solid Cu less than expected

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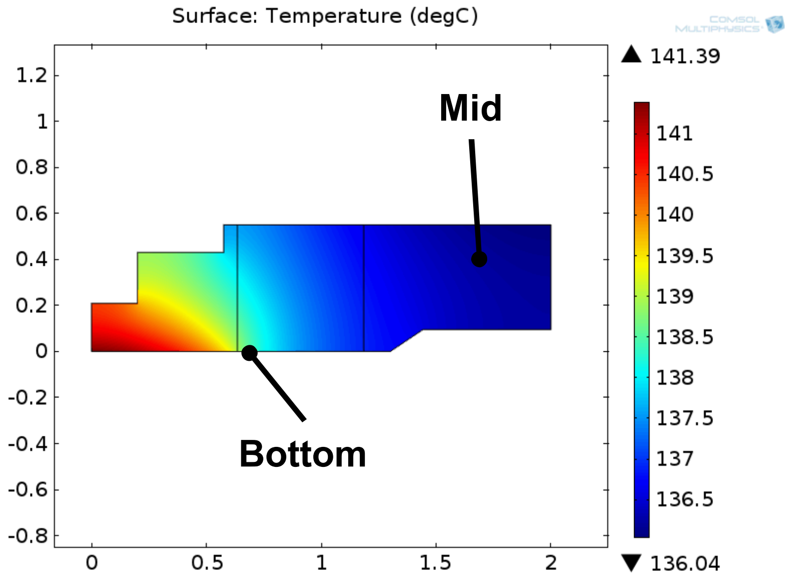
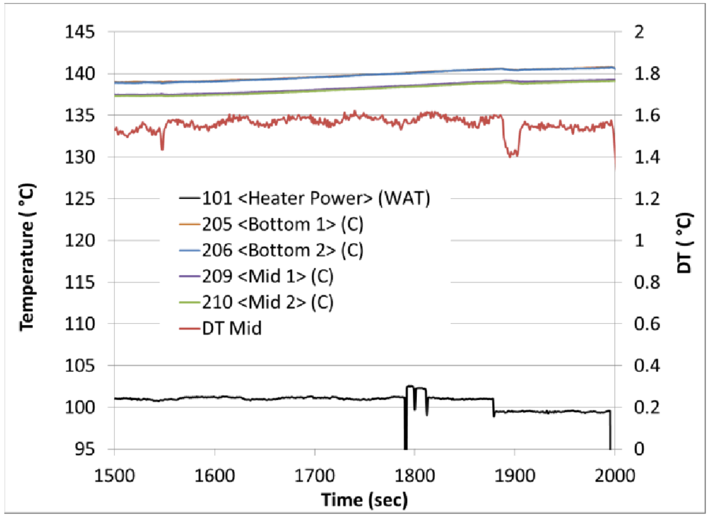
Modeling and experiment used to determine Cu baseplate Rth





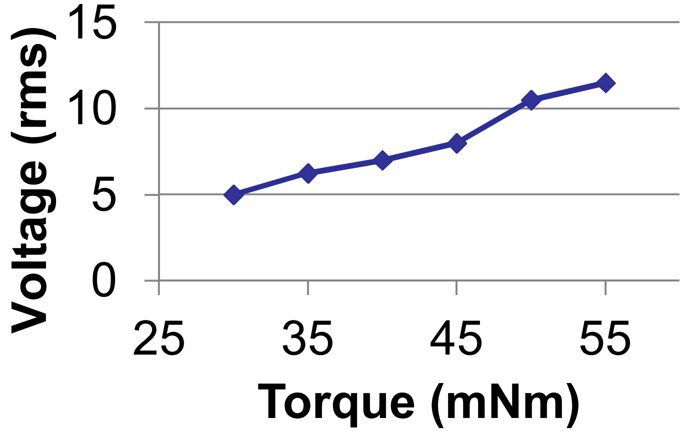
	Solid Cu	Vapor Chamber
ΔT @ 100W	1.9 ℃	1.2 ℃
Rth (C/W)	0.04	0.02?

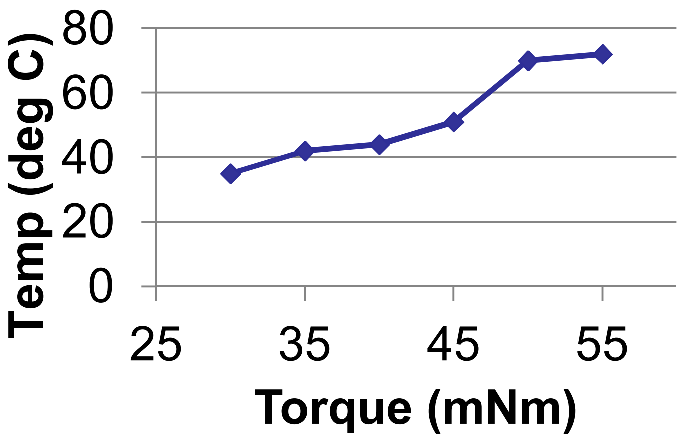
V5 device compared to standard and after-market CPU coolers

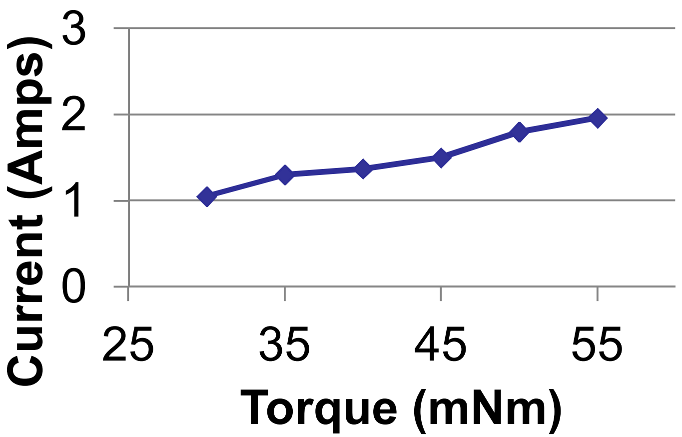
	V5 (2500 rpm, 10 μm gap, Vap. Ch.)	V5 (3000 rpm, 5 μm gap, Vap. Ch.)	Intel i7 OEM cooler (Nidec F10T12MS1Z7)	Noctua NH-D14
Rth (C/W)	0.156	0.12	0.252	0.10
Impeller	0.084	0.073		
Air gap	0.052	0.027		
Baseplate	0.02	0.02		
Power consumption (W)	~5	~10	3.6	2.3
Noise (dBa)	48	49	28.5	30.5
Dimensions (mm)	100X100X46	100X100X46	100X100X62	140X158X160
Volume (cc)	460	460	620	3540
Specific cooling capacity (W/C/cc)	0.014	0.018	0.0064	0.0028
Price ($)	?	?	$12	$80

Motor can overcome start-up torque with reduced contact area

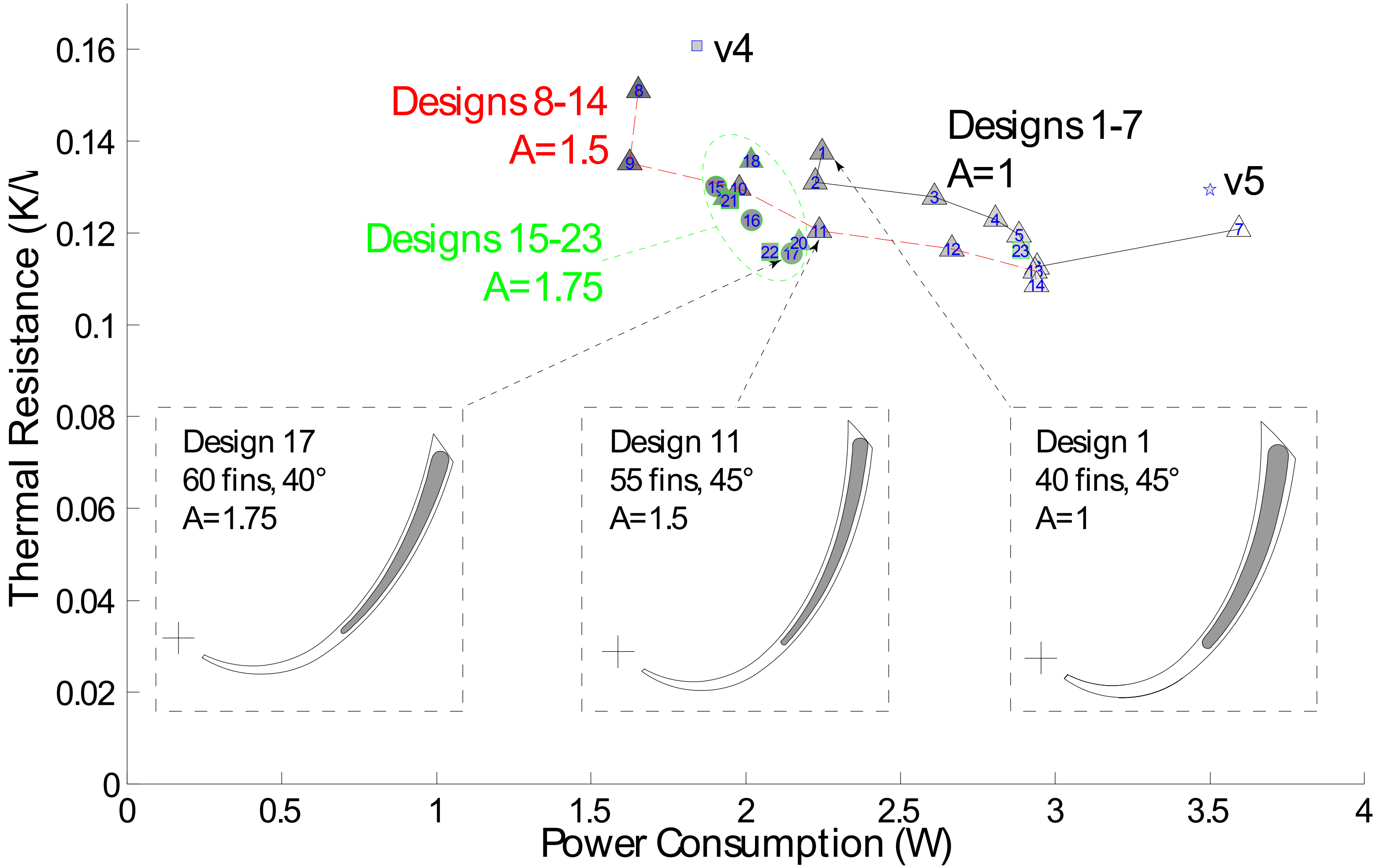
- Motor can produce up to 55 mNm
  - potential higher but experienced voltage saturation from amplifiers
- 3-phase motor with 34 gauge windings ramped from 0 to 300 rpm in 1.5 seconds





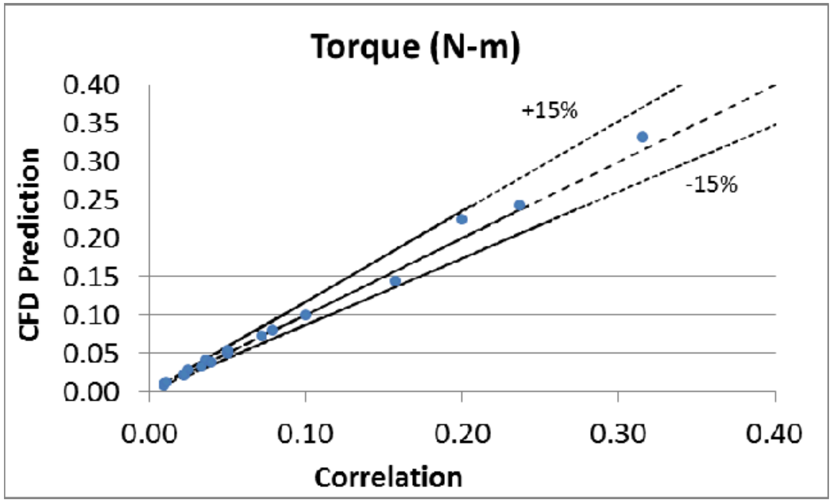


40 different permutations of the impeller geometry were modeled to find an improved design

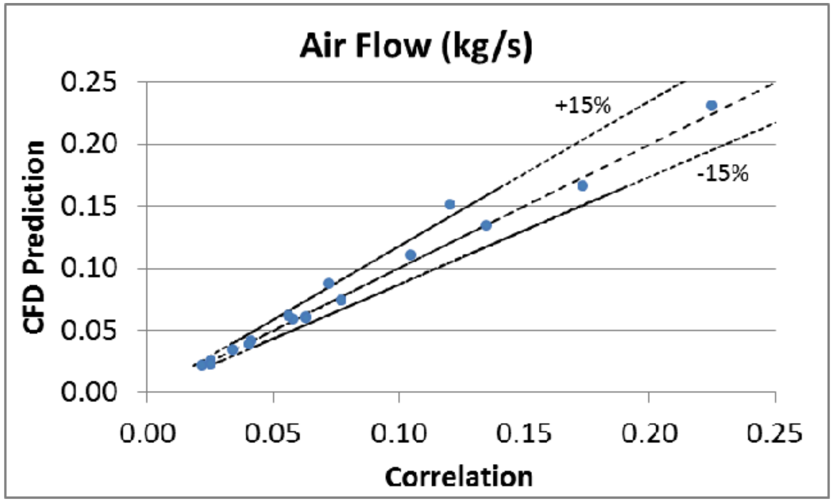


Correlations based on CFD studies predict impeller performance to within ±20%

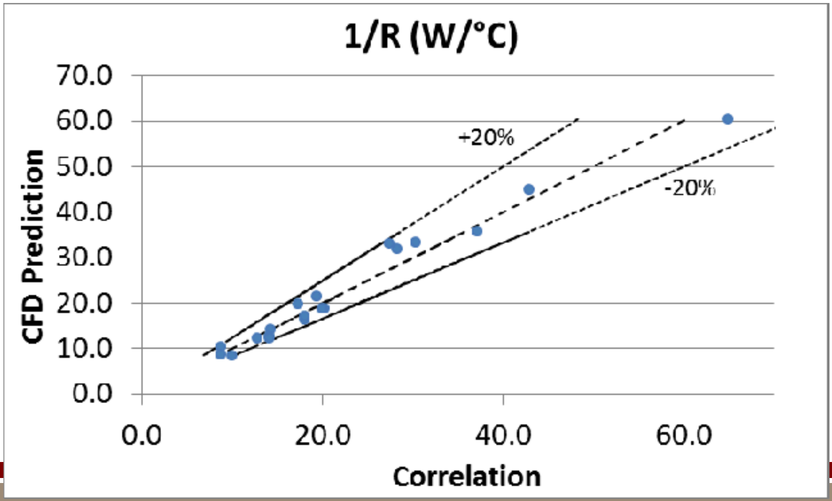
$$\tau = 4.8 \times 10^{-12} h \omega^2 d^4$$



$$Q = 1.16 \times 10^{-7} h^{0.9} \omega^{1.1} d^{2.25}$$



$$\frac{1}{R} = 2.82 \times 10^{-3} h^{0.5} \omega^{0.6} d^{1.8}$$



Note, since *Power* = τ x ω:

$$P = 4.8 \times 10^{-12} h \omega^3 d^4$$

ω in rad/s
h in cm
d in cm

Ten Demonstration Units will be completed by January 2014

Most components are complete and ready to assemble

Impellers:

- 5 are complete
  - machined, coated, motor rotor installed
- 6 more have been machined, not coated

Vapor chamber baseplates:

- 9 are complete, 1 more in progress
  - Machined and coated

Shafts:

- 10 are complete

Motor Stators:

- 3 wound and ready