Select Variables Affecting Thermal System Design of a Liquid-Cooled Stator

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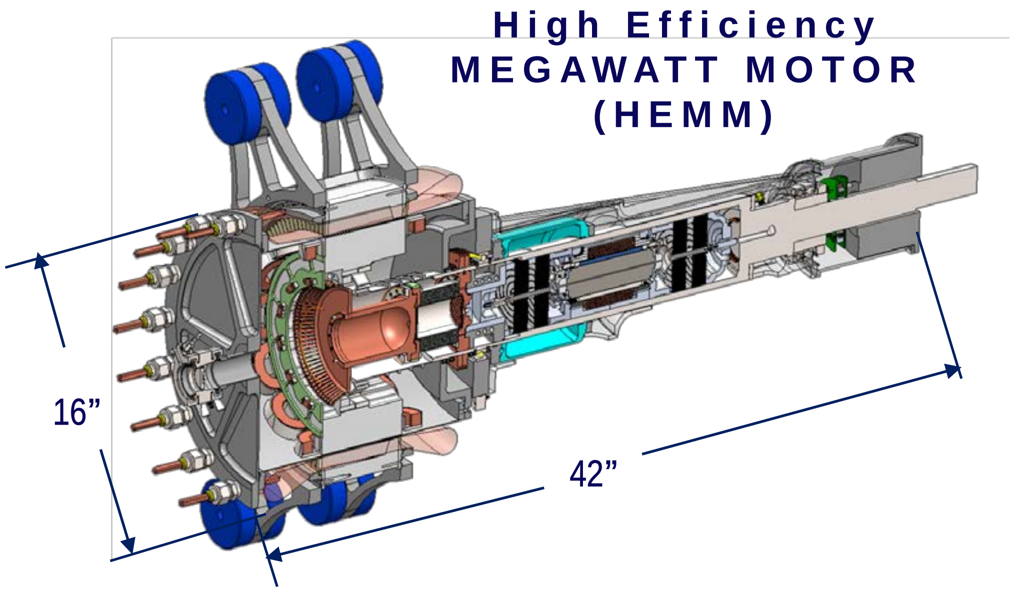
High Efficiency Megawatt Motor (HEMM)

Challenge: Develop a motor for Electrified Aircraft Propulsion with greater than 98% efficiency and a specific power greater than 16 kW/KG (9.8 hp/lb)

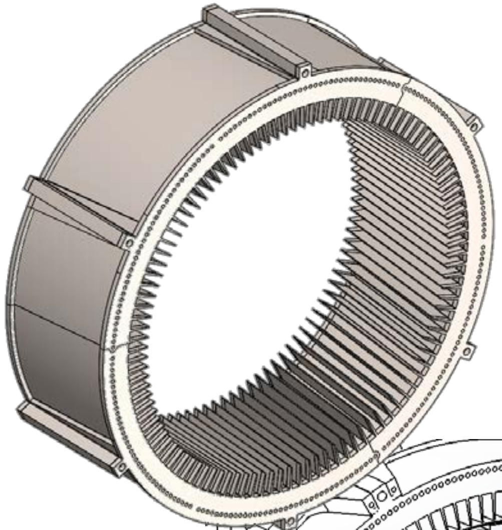
- **Solution**: Synchronous wound field machine, with a superconducting rotor that does not require an external cooling system. A crycooler is integrated into the motor.
- **Key Feasibility Items:**
  - Wound field stator
  - Superconducting DC rotor
  - Integrated cryocooler
- **Benefits:**
  - Operates like any traditional (non-superconducting) motor
  - Direct drive (no gearbox)
  - Can be shut down as opposed to perm. magnet

33% of the loss comes from stator

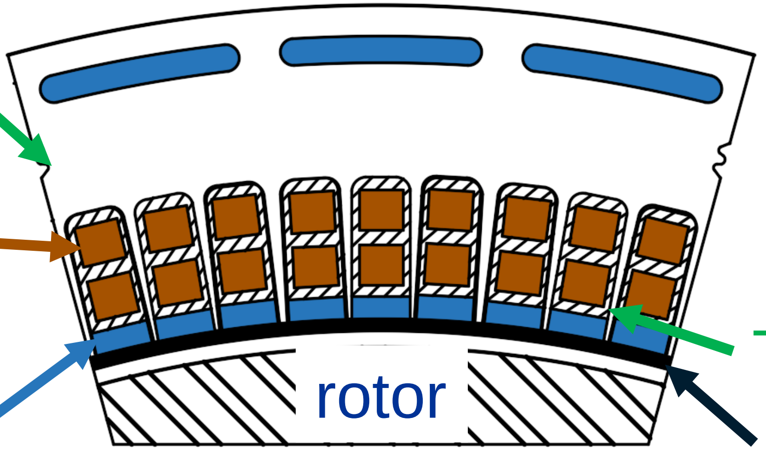


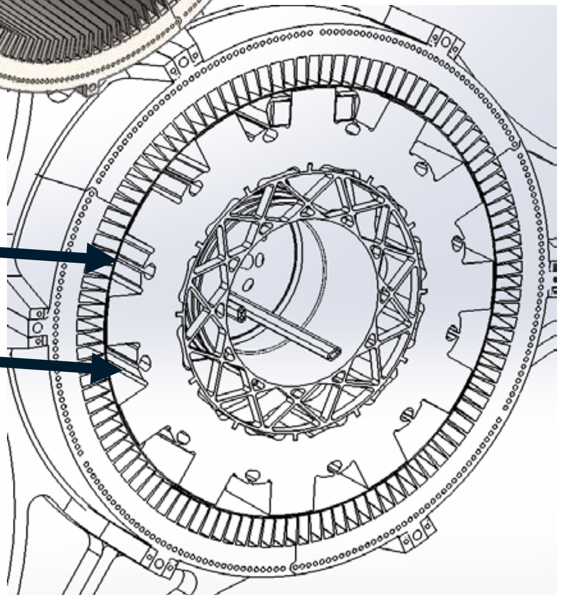
For more detailed information on other aspects of HEMM please view other presentations in this session: EATS-20, Developments of the NASA High Efficiency Megawatt Motor

HEMM stator detail



- Purpose of thin teeth:
  - Teeth alleviate shear stress problem in coils
  - Provide support/location for fabricaton
  - Form cooling channels between Litz wire and the vacuum tube
  - Updated design the teeth are plastic to reduce losses
- Fluid cooling path goes through the air gap of the motor.
  - Cool ID of coil pack
  - Keeps ID at 60 °C to reduce radiation heat transfer to rotor





Szpak *et al*, “High Efficiency Megawatt Motor Thermal Stator Preliminary Design”, EATS-20 Session, 2020
Scheidler *et al*, “Electromagnetic Redesign of NASA’s High Efficiency Megawatt Motor”, EATS-20 Session, 2020

Why did we write this paper?

Continued development of the entire motor

- Verifying design
- Developing fabrication techniques

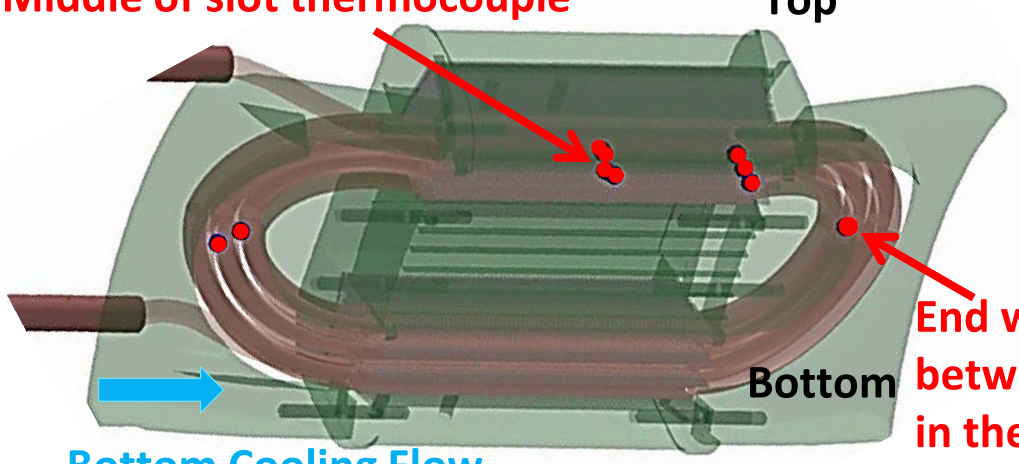
Lessons learned

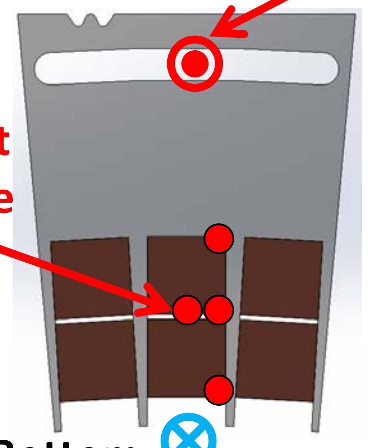
- Built 3 statoretts (sub-scale stator like test devices)
- 3rd generation statorette varied significantly from performance of first two statorettes
- Variation in performance forced an in depth investigation of a number contributing factors

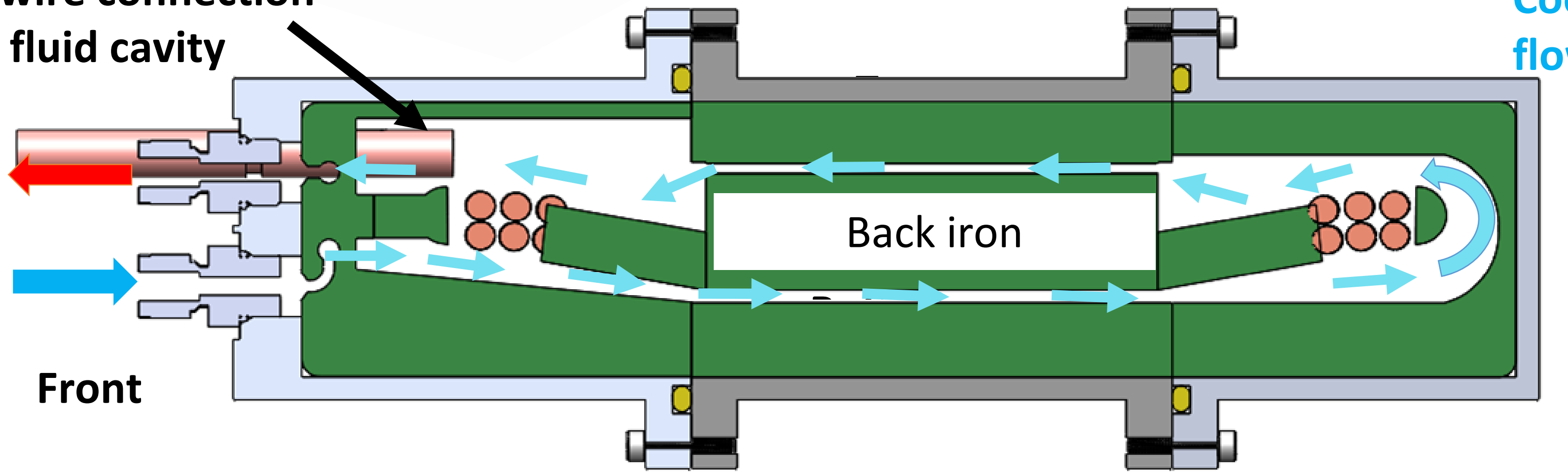
Communicate thoughts about impacts of non-primary design aspects

- Motor design is highly multidisciplinary
- Fabrication details matter
- Details of cooling matter

Statorette







Woodworth, A., Sixel, W. A., Edwards, R., Jansen, R., McCormick, S., Robbie, M., Smith, A., Naghipour, P., and Shin, E. E. "Thermal Analysis of Potted Litz Wire for High Power Density Aerospace Electric Machines," *AIAA Propulsion and Energy 2019 Forum*. 2019, p. 4509.

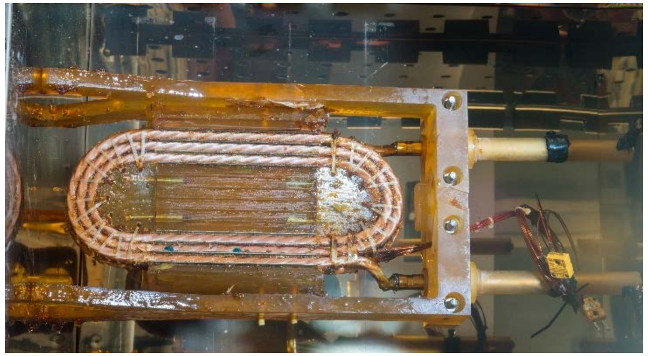
Statorette materials details

- Slots made of laminated steel
  - Similar transverse thermal conductivity (~27 W/m·K) as soft magnetic back iron
- Litz wire
  - Type 8 (AWG 3 equivalent)-8 mm x 8 mm square
  - 6000 AWG 40 wires (~80 μm diameter)- 4 μm polyimide coating
  - Double Nomex wrap (high voltage insulation)
- Potting material
  - 2 part high temperature (260 °C) epoxy, thermal conductivity =1.3 W/m·K (no fillers)
- Plastic
  - 3D printed (stereo lithography)
  - Thermally insulative
- Colling fluid: silicon oil
  - Designed for use in high voltage transformers (high dielectric breakdown)
  - High flash point
  - Significant thermal and viscosity data available

Statorette’s performance

Statorette #1

Statorette #2



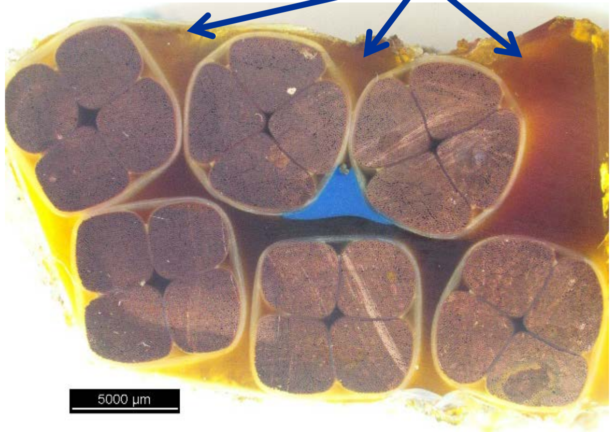
Statorette #3

	Statorette #1	Statorette #2	Statorette #3
Conditions	325 A, 11.8 lpm	400 A, 11.8 lpm	400 A, 11.8 lpm
Predicted (°C)	N/A	125	97
Actual (°C)	122	128	**145**

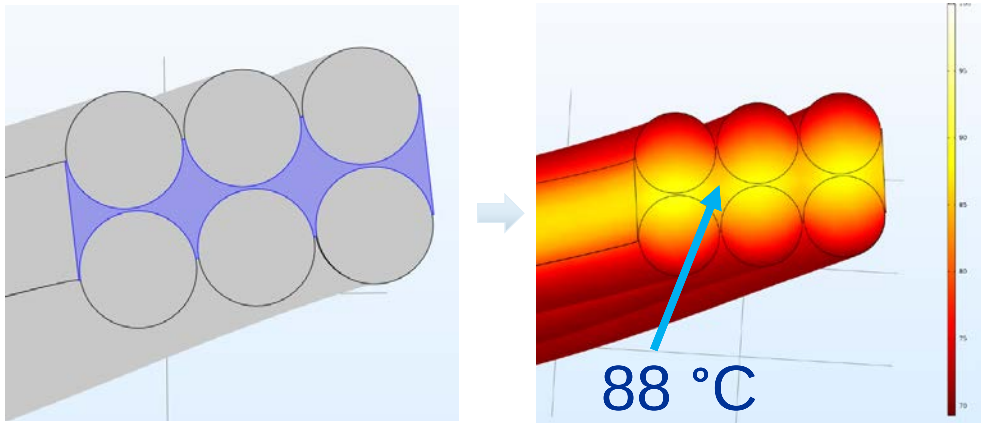
Data and predictions for thermal couple embedded in back side end wingdings

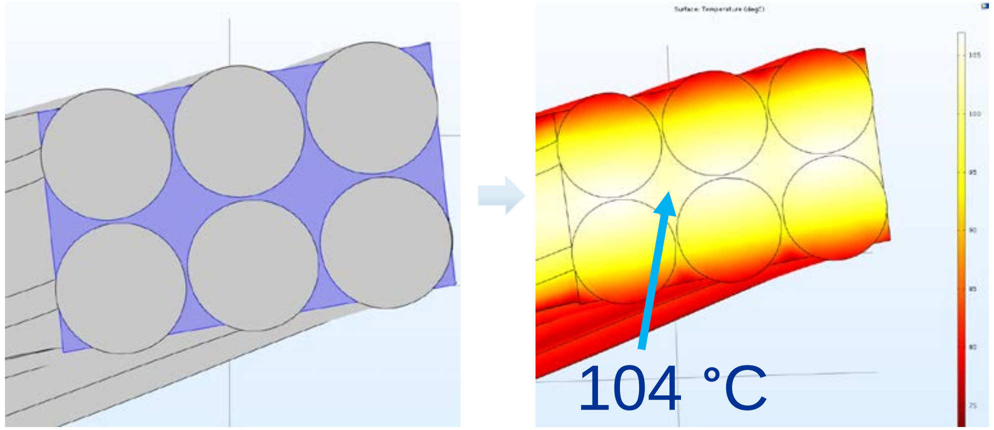
Potting-3rd generation statorette results

Excess epoxy



Second Generation

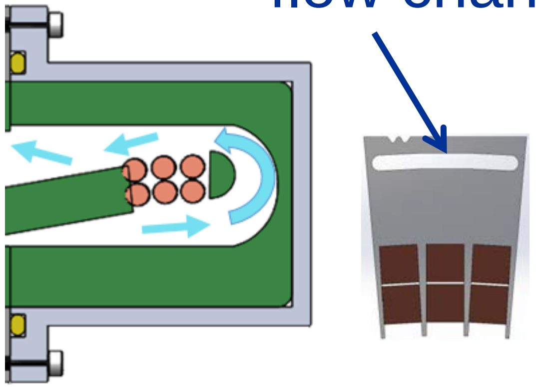




Excess epoxy does have impact!

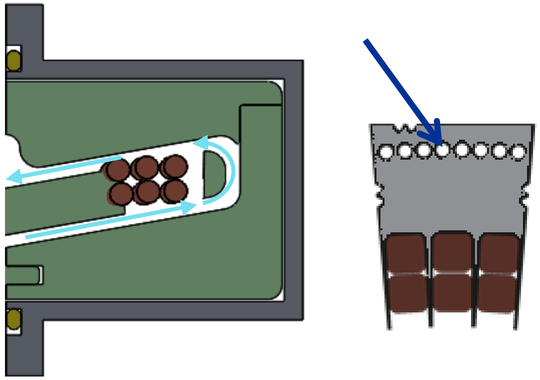
End winding flow cavity

Back iron
flow channel



Large cavity
(statorette #1 & #2)

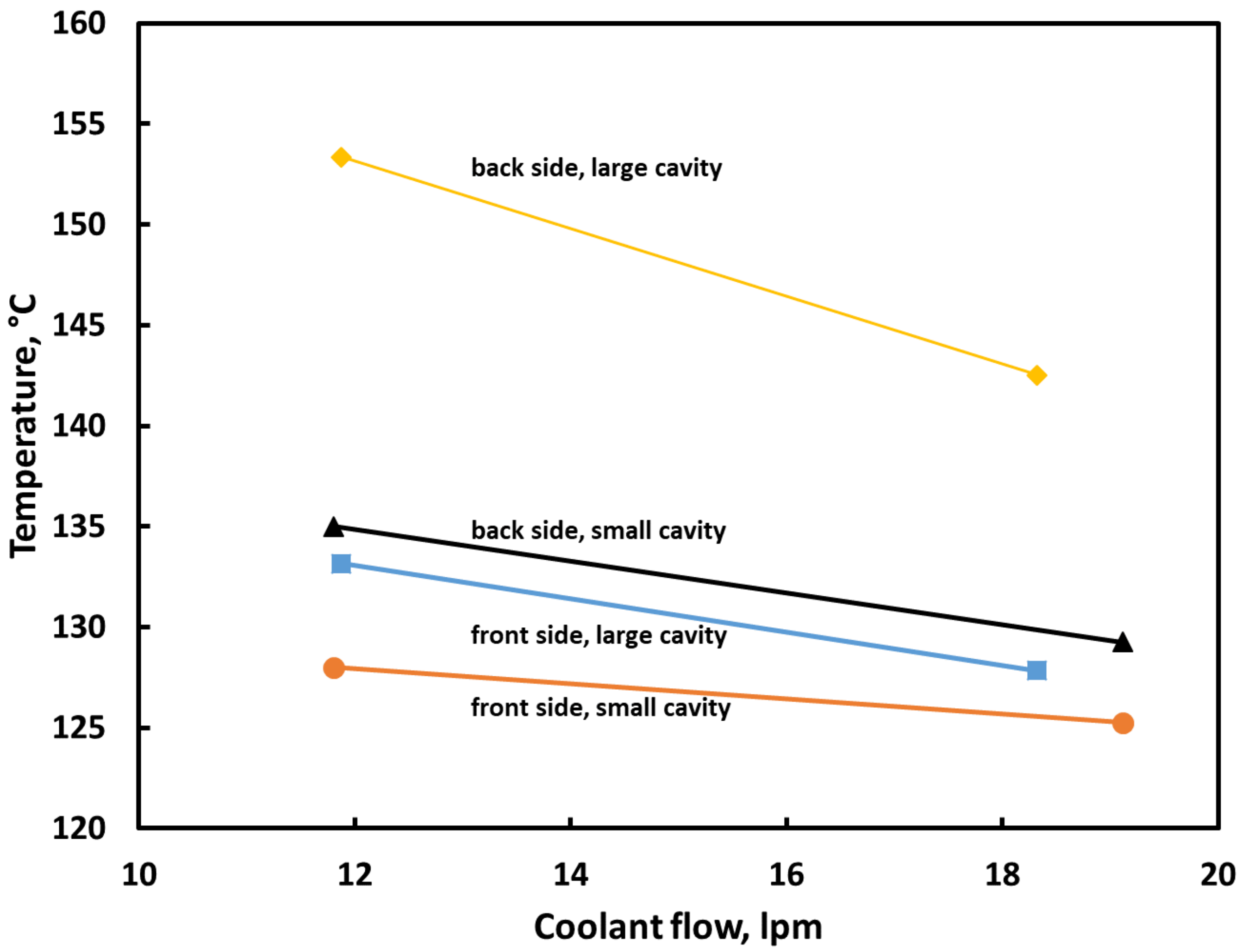
Back iron flow
channels



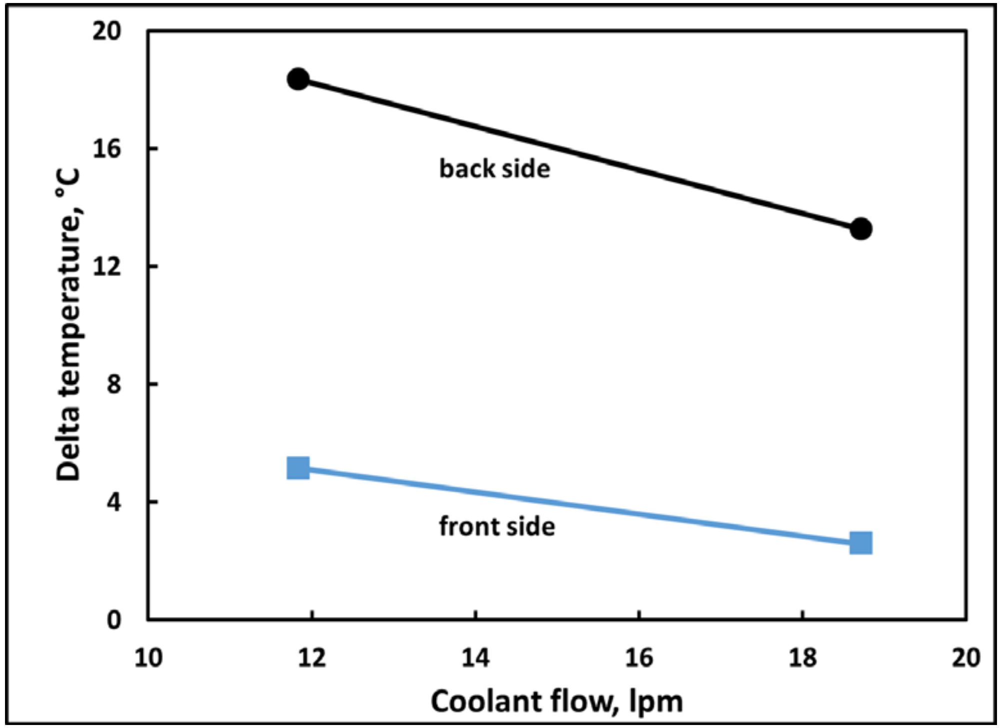
Small cavity
(statorette #3)

A set of inserts mimicking the large cavity were made for statorette #3 to better understand impacts of the fluid volume change

Fluid cavity impact

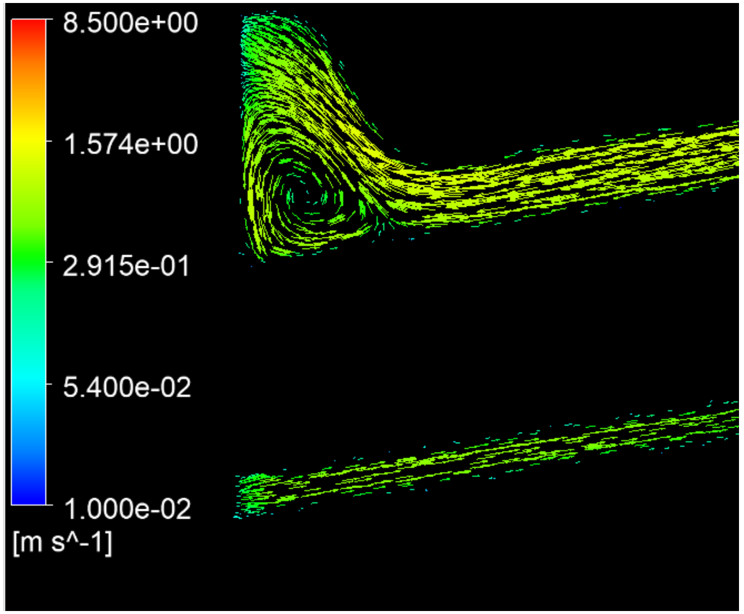


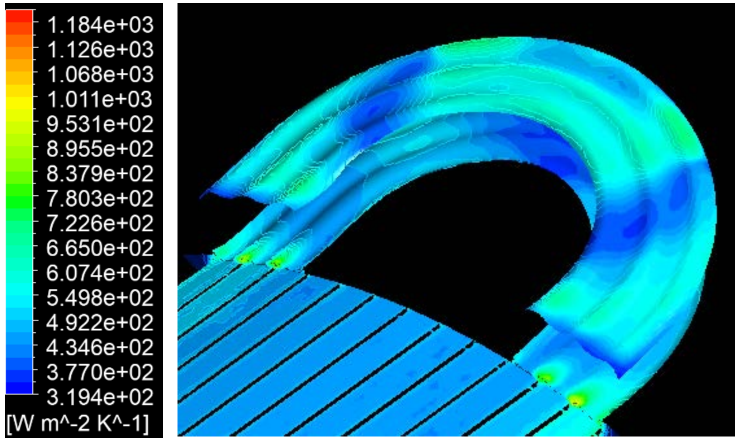
Change in temperature between small and large cavities



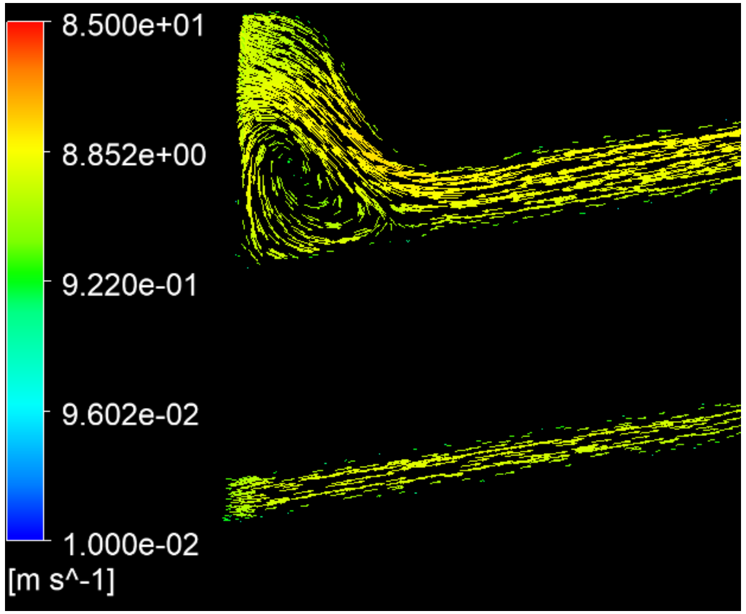
Test run at 400 A DC

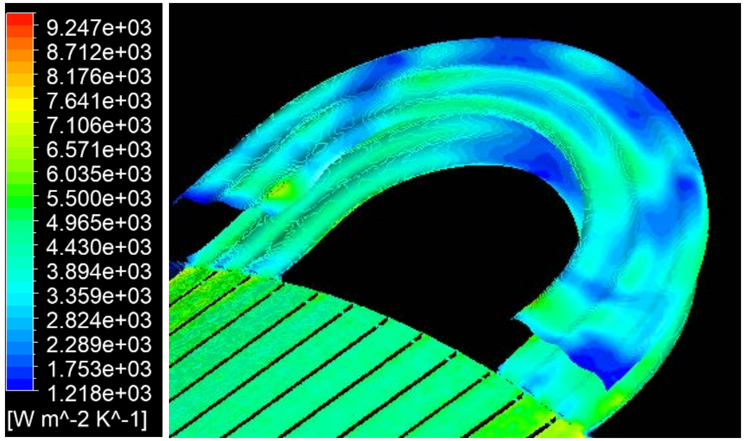
Fluid velocity impacts on heat transfer



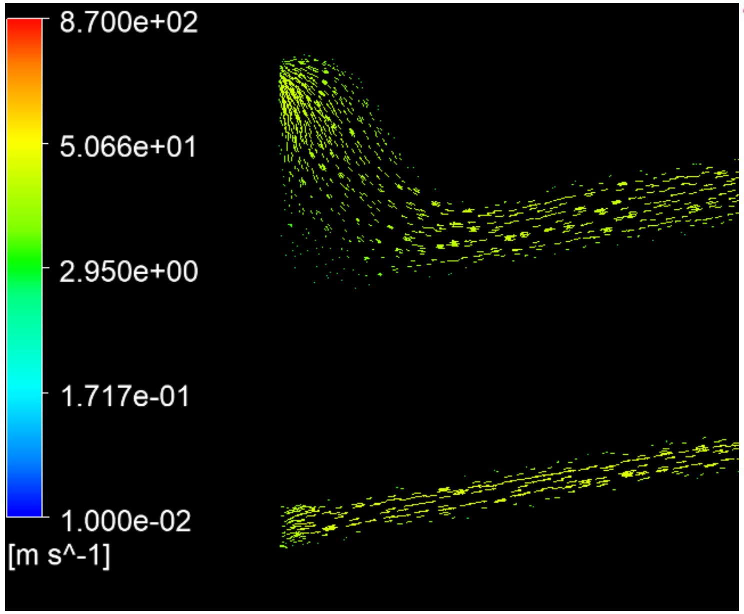


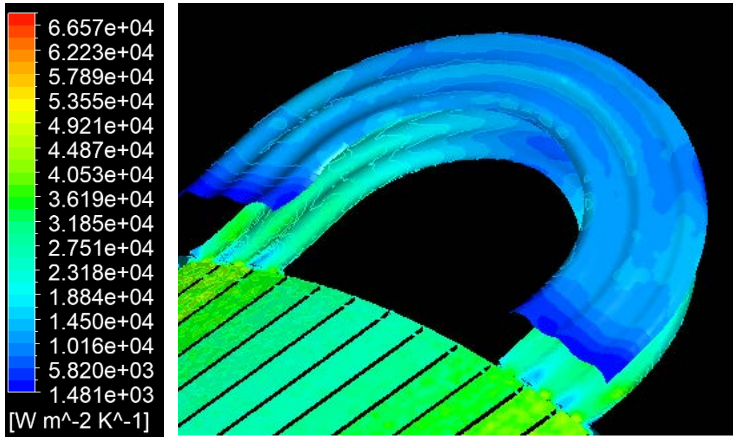
Statorette flow rate: 10 lpm
Channel Reynolds #: 857





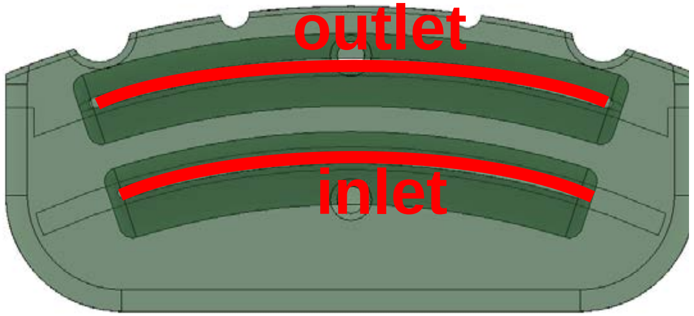
Statorette flow rate: 100 lpm
Channel Reynolds #: 8570



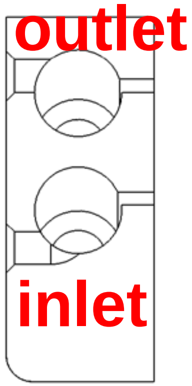


Statorette flow rate: 1000 lpm
Channel Reynolds #: 85700

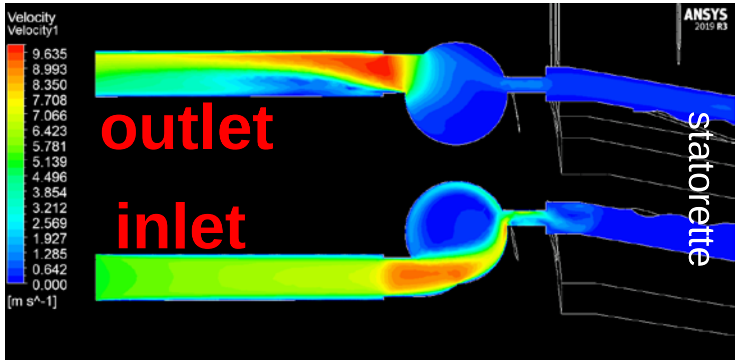
Thoughts on viscosity



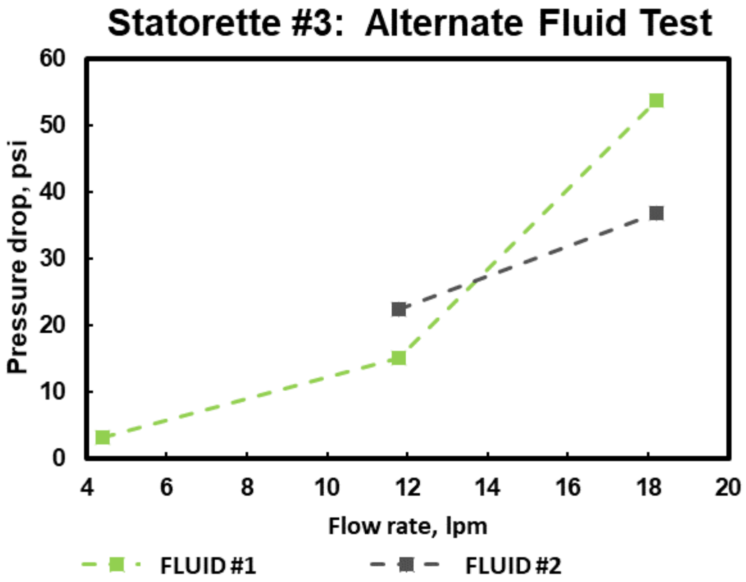
(a)



(b)



(c)



Silicon-based cooling fluid properties at 60 °C

Fluid	Density [kg/m³]	Viscosity [cSt]	Thermal conductivity [W/m·°C]	Specific heat [J/kg·°C]	Approx. Prandtl number
FLUID #1	985	33	0.150	1696	367
FLUID #2	900	5.4	0.127	1680	64
FLUID #3	935	3.6	0.134	1507	38
FLUID #4	918	2.7	0.134	1800	33

FLUID #1: Clearco Products Co., I. "STO-50 Silicone Transformer Oil Product Information Sheet."
FLUID #2: Clearco Products Co., I. "PSF-10cSt Silicone Heat Transfer Fluid." 2019.
FLUID #3: Corporation, D. C. "Syltherm 800 Technical Data Sheet." 1997.
FLUID #4: Clearco Products Co., I. "PSF-5cSt Silicone Heat Transfer Fluid." 2019

$$Reynolds\ \text{number} = \frac{u \cdot L}{\nu}$$

- u = fluid velocity
- ν = viscosity
- L = char. length dim.

- Pressure drop across statorette limited flow
- Going to lower viscosity fluid pays off
- Fully developed turbulent flow will require
  - Flow >100 lpm
  - FLUID #3 or FLUID #4 due to lower viscosity

Other checks

- A significant number of thermocouples were placed (not previously shown) in the statorette
  - Helped identify the non conformance to predictions
  - Gave confidence in results
  - Thermal soak test proved thermocouples were functioning properly
- Checked for flow impediments
  - Debri
  - Bubbles
  - Fabrication defects

Built confidence the fabrication process and the validity of the results

Summary/Conclusions

- Potting
  - Excess epoxy does have a real effect
  - Need to tune potting process
- Cooling
  - Reduction in cavity size does have a positive impact on cooling
  - Need to reach fully developed turbulent flow in order to realize maximum cooling
    - This will require significant fluid flow
  - Influences of fluid viscosity
    - Flow necessary to develop a fully turbulent flow
    - Pressure drop across the system
    - Required pumping power
- Other
  - A significant instrumentation is necessary to understand such a complex system
  - Checking a number variables built confidence in the results

Secondary design considerations do have a significant impact on performance!

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Thank you!

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