Selecting an Encapsulant for an Aerospace Superconducting Machine

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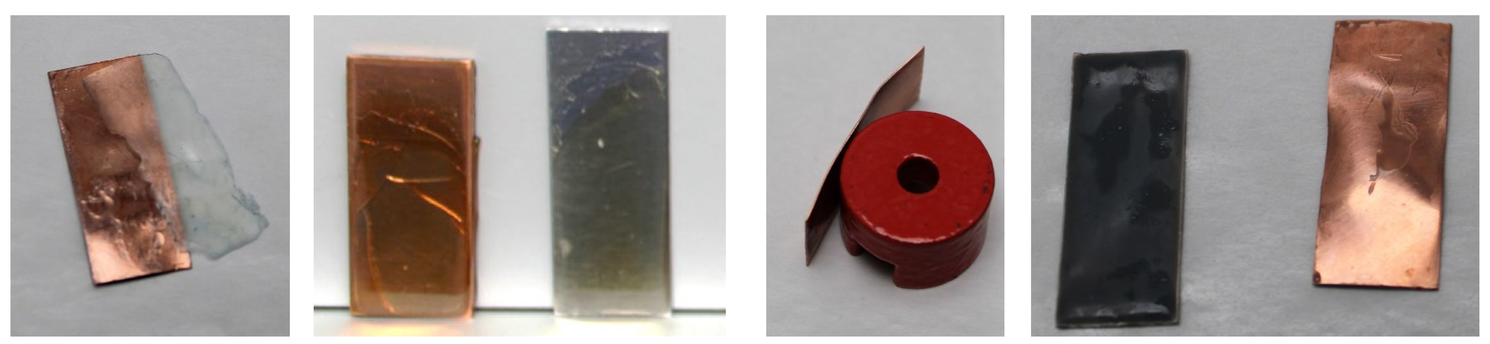
Abstract—Achieving larger benefits from electrified propulsion in single aisle aircraft (the largest commercial aircraft market segment) necessitates that a significant fraction of their 20 MW or greater propulsion system be electrified. These aircraft would require up to 10-20 of today's state-of-the art machines, which have been demonstrated up to 2.5 MW for aerospace use, and could benefit further from 5 MW+ designs. However, when conventionally cooled, high power density machines still produce a significant amount of waste heat, translating into heavy thermal management and detracting from system benefits. Highly efficient fully superconducting electric machines (or those with a cryogenically cooled, high purity copper or aluminum stator) are a possible solution but have multiple barriers to overcome. One such barrier is the durability of superconducting windings. Superconductors are typically brittle, and encapsulants used to hold windings in place are a significant source of stress due to mismatches in coefficient of thermally induced contraction between ambient and operational temperatures (20 to 77 K). Lack of compliance between the materials at operational temperatures also adds significant stress. These encapsulants also form a thermal barrier that can be detrimental to cooling the superconductors. This work describes an initial study of commercially available encapsulants as it relates to superconducting machine applications, along with initial modeling of thermal stress in superconducting windings for a superconducting or cryogenically cooled stator in a 5 MW electric machine.

Initial Down Selection

- 7 commercial epoxies were investigated as possible encapsulants for cryogenic application in a superconducting (SC) motor
- Epoxies were coated onto thin Al and Cu strips (simulating SC or Litz wire elements) and then thermal cycled between LN2 to room temperature (R.T.) 5 times
- Three epoxies failed three different ways



Delamination Cracking Warping

Down Selection

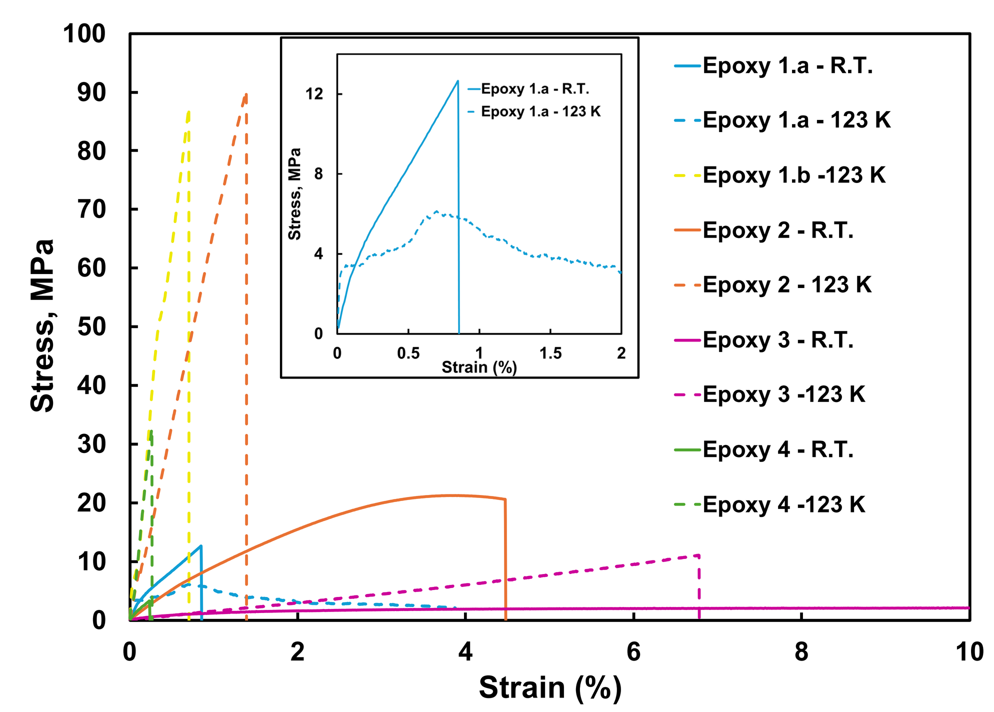
Trade Space

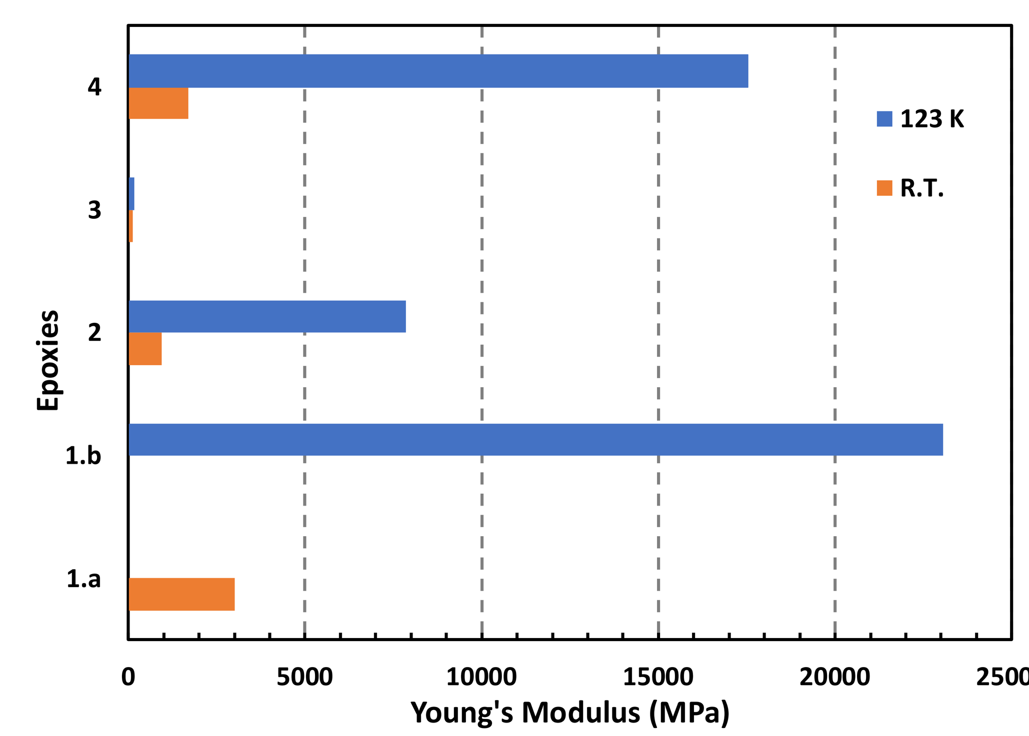
- Viscosity determines the ability to infiltrate into micron-sized gaps
- Thermal conductivity limits the ability of the material to aid in removal of heat
- CTE determines thermally induced stress experienced in the brittle conductors
  - CTE for the conductor is expected to be 15-30 ppm/°C
- Young's Modulus also contributes to stress experienced in the brittle conductors

Epoxy	Filler	Viscosity (kcP)	Thermal Conductivity, W/m-K (R.T.)	Coeff. of Thermal Expansion (ppm/°C ±1.5/°C ppm, 153 K to R.T.)	Cure Temperatures (°C)
1.a (catalyst 1)	Al_2O_3 + C	14	1.26 ± 0.02	16	R.T. / 45 / 65
1.b (catalyst 2)	Al_2O_3 + C	25	1.48 ±0 .25	33	80 / 100/ 120
2	None	0.02	0.28 ± 0.01	62	65
3	None	14*	0.34 ± 0.04	26	R.T. / 65
4	Al_2O_3	890	1.42±0.01	34	R.T.

- *Artifacts of the viscosity measurement caused this value to be significantly higher than the material visually behaves (visually behaves more like motor oil ~0.5 kcP)
- R.T. = Room Temperature

Mechanical Testing





Summary of Mechanical Testing

- Epoxy 3 retained the lowest modulus even at cryogenic temperatures (important to minimize stress on the conductors in the application)
- Epoxy 2 did not perform as well as epoxy 3 but was still 2nd best
- Epoxy 1 performed poorly in mechanical testing and was difficult to remove from molds
- Highest Young's modulus is in the filled epoxies (1 & 4)

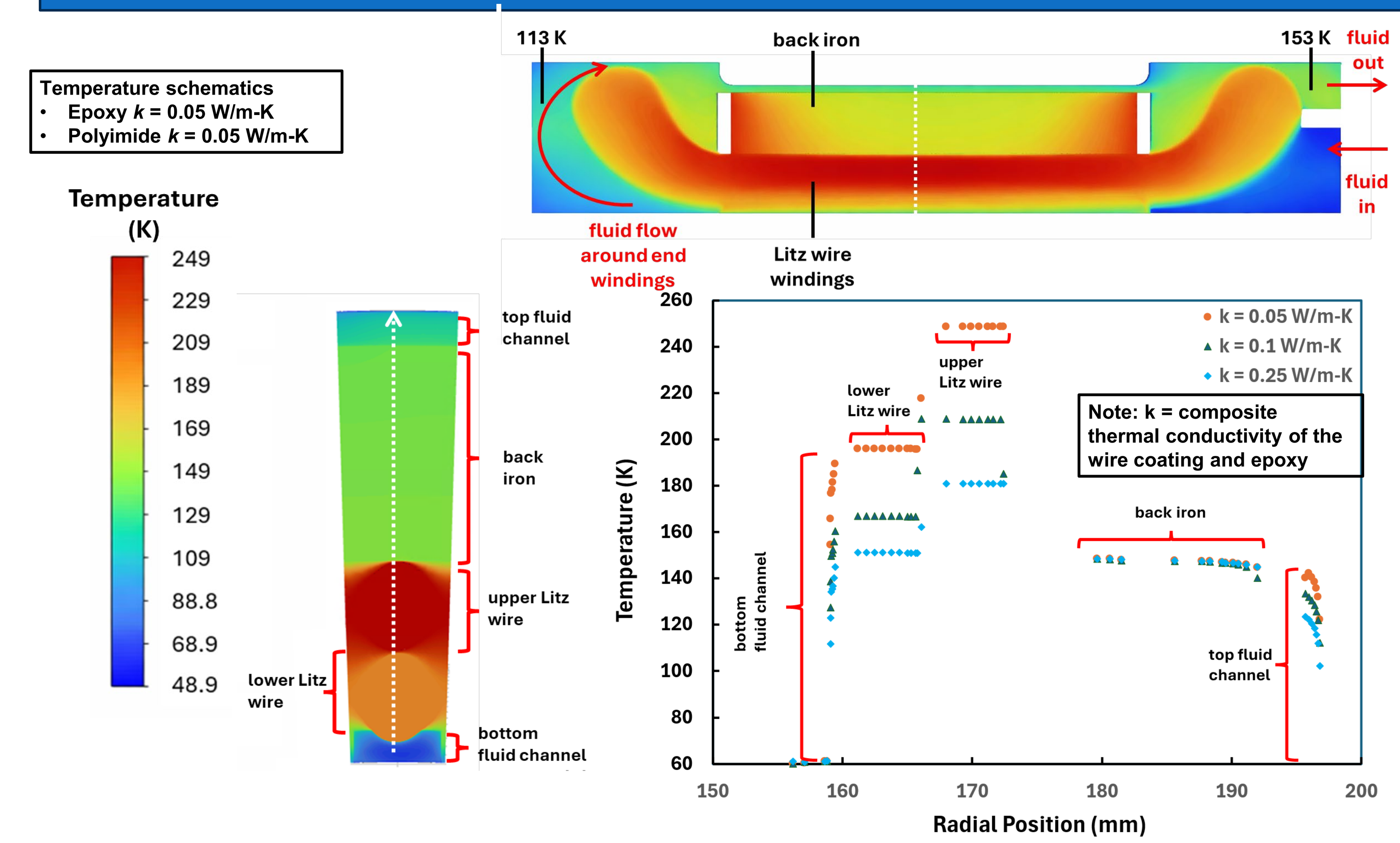
Takeaways

- Properties vary greatly from R.T. to 123 K
- The trade space is complex and will influence design and fabrication

Thermal Modeling

Purpose: To explore the impact of a material's properties on cryogenic cooling

- Re-utilized a previously developed conjugate CFD model of a single slot of a stator
  [A. Woodworth, W. Sixel, R. H. Jansen, and G. M. Szpak, "High Efficiency Megawatt Motor Stator Thermal Performance," in AIAA Aviation Forum and Ascend 2024, 2024]
- Type 8 Litz (AWG 3 equivalent) wires constructed of 6000, 40 AWG strands coated with a ~10 µm thick polyimide (magnet wire insulation) coating all potted in an epoxy
- Material thermal conductivities set to reflect cryogenic operation
- 60K He is working fluid, 0.2 bar and 0.00577 m^3/s
- Varied the composite thermal conductivity of potting material and polyimide coating to probe sensitivity



Summary of Modeling Results

- He increases significantly in temperature as it flows around the winding indicating that a single pass design is not optimal for maintaining cryogenic temperatures
- Large temperature difference between Litz wire bundles demonstrates the need for a cryogenic operation specific design
- 2X thermal conductivity has a significant impact on Litz wire temperature but further increases seem to hit a point of diminishing returns

Takeaways

- A design specific for cryogenic operation is required for the desired temperatures
- A point of diminishing returns exist for increases of thermal conductivity in encapsulation/insulation

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