Experimental Validation of a Conduction Cooled HTS Motor

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Motivation – MEA & AEA

- Design toward More Electric Aircraft and All Electric Aircraft
- Conventional electric motors
  - Exhibit low power density
  - Reached an optimum in performance
- High power density needed for airborne application
  - New technology is needed
  - High temperature superconductivity may provide a very good solution
Outline

• Motor design
  – Electro magnetic design utilizing HTS components
  – Field Cooling method of flux trapping

• Cooling of the motor inductor
  – Conduction cooling apparatus design
  – Cooldown schedule

• Simulation results using Comsol multiphysics software
  – Transient cool down including 3-stage cooling
  – Steady-state verification on heat loads

• Experimental results
  – Proof of design principle
  – Validation of cooling results

Revolutionize Aviation
HTS Motor Design

- Motor designs use HTS components
  - Wound coils of HTS tape
  - Bulk material with trapped flux

- Increase power density
  - HTS materials can decrease size and weight of motors
  - Stronger magnetic fields than conventional motors can be generated

- Cooling requirements
  - Cooling HTS components to cryogenic temperatures
  - Maintaining steady state operation
  - Thermal design to limit heat loads
HTS Motor for Aeropropulsion

• Motor designed for Cessna-type aircraft
  – 160 HP
  – Large Power Density

• HTS Motor
  – Superconducting Inductor
  – Air-Gap Armature
  – Inverse configuration
    • Non-rotational (HTS) inductor (cryocooled)
    • Rotating armature (room-temperature)
  – Need as high a power density as achievable

• Focus on cooling inductor
  – Cooldown and maintaining steady-state operation
  – Conduction-cooled
  – Air-cooled armature not studied
Superconducting Motor with HTS components for Aeropropulsion

Inductor Steady State operating temperature is ~30K
Armature Steady State operating temperature is ~400K
Vacuum cryostat separates inductor from armature
3 BSCCO Pancake Coils
   - 80mm inner diameter
   - 140mm outer diameter
   - 25mm thickness
   - Coils wound of Bi-2223 and Kapton tape

8 YBCO bulk plates
   - 30x54x5mm

Overall inductor dimensions as shown
2mm gap between pancake and YBCO plate
YBCO trapped flux from BSCCO pancakes

YBCO plates red
BSCCO pancakes blue
Conceptual E-M Design and Flux Trapping

I field

I magnetization

I operation

YBCO Plates cool down

Flux Trapping and Flux Concentration

Time
Flux Trapping and Temperature

Flux Trapping and Flux Concentration

I field

I magnetization

I operation

YBCO Plates cool down

Need to keep a substantial temperature gradient across the YBCO bulk/BSCCO coil gap before trapping flux in the bulk.
Cooling Requirements

- Cool inductor from 300K to operational temperature ~30K
- 3-Stage Cooling allowing for flux trapping
  - Cool BSCCO pancakes to operational temperature while maintaining YBCO plates above critical temperature
  - Apply field to YBCO plates, then cool to ~30K
- Maintain Steady State operation
  - Calculate/ameliorate the heat loads on inductor (shown below)
  - Maintain operational temperature of HTS components

- Steady state heat loads
  - Radiation 0.2 Watts
  - “Equivalent Resistance” of the Wire 1.8 Watts total for Pancakes
  - Resistive connections between coils 0.02 Watts total
  - Conduction losses from current leads 5.4 Watts \( \sim 7.4 \text{ Watts} \)

- Minimize contact resistances
Apparatus construction begins with a cylinder. YBCO single crystal plates and BSCCO wound tape pancakes are added. Rings of G10 provide thermal resistance for the YBCO plates. The bulk YBCO plates are then added. The final design connects to the cryocooler.
Modeling the Conduction Apparatus & Inductor

- 3 Dimensional Modeling
- Comsol Multi-physics – General Heat Transfer Module
  - Transient
    - Cooldown time
    - 3-stage cooling
  - Steady State
    - Maintaining operating temperatures
    - Heat loads at cryogenic temperature
- Determine time to cooldown and temperature distribution during 3-stage cooling
- Steady state temperatures of the HTS components (incl. hot spot)
Initial and Boundary Conditions on Inductor

- $T_i = 300K$ of inductor
- Cryostat temperature is 400K
- Radiation heat load is equally applied on entire surface of inductor
- Conduction heat load from current leads is on the cryocooler, not the inductor
- Thermal conductivity and specific heat $= f(T)$
- Internal heat generation loads in pancakes is applied over the entire volume of the pancakes
- $P_{\text{cryocooler}} = f(T)$
- GM Cryocooler Cryomech AL-330
Transient Model Results

- Cool down 300K - 30K
- Temperature range is 150K – 10K
- Video starts ~ 3 hours after cooling begins (T>150K)
- Two simulations combined so time on video is slightly inaccurate (before and after YBCO heaters are turned on)

Source File: total cooldown.wmv
Transient Model Results (cont.)

- Timeline of the YBCO and BSCCO hotspots
- Cooldown time ~6 hours

**Inductor Cooldown**

- YBCO plates above $T_C$
- Pancakes below 40K
- Temperature Gradient Achieved

![](Diagram.png)
Steady State Simulation Results

ACCEPTABLE TEMPERATURE GRADIENT ACHIEVED IN STEADY STATE

$\Delta T = 2.2 \text{ K from cylinder top to cylinder bottom}$

Hot spot on YBCO
($\Delta T = 3.5 \text{ K from cylinder}$)

Hot spot on pancakes
($\Delta T = 2.5 \text{ K from cylinder}$)
Modeling Summary

- Cooldown of the inductor ~6 hours
- YBCO heaters and G10 allowed for temperature gradient
- 3-stage cooling was successful
- Temperature gradients in BSCCO pancakes during steady state operation were acceptable
- Conduction cooling via apparatus is viable
Construction of HTS inductor mock-up

- Validate simulations with full-scale thermal mockup
  - Full-scale thermal mockup is constructed
  - Materials similar to the HTS materials
- Machining, winding, and construction done at Florida State University labs (CAPS) and the National High Magnetic Field Lab
Heat Loads in Experiment

- Heaters in the pancake
  - Simulate the “Equivalent resistance” of the wire
  - Nichrome tape wound in the copper and Kapton pancake
  - ~32 Ohms/m
  - 3 pancake heaters connected in series
  - 0.6 Watts per pancake

- YBCO heaters
  - Nichrome wire in Kapton tape
  - 8 pancakes connected in series
  - ~2 ohms each
  - Sealed and attached in epoxy
  - Produces ~ 1 Watt per YBCO plate
Experimental Procedure

- Full-scale mock up will be tested in cryostat
- Cryostat under vacuum with LN$_2$ jacket
- Conduction Cooled from Cryocooler
- Steady State and Transient experiments
- Thermal sensors (RTDs) to measure temperature gradients in cylinder and HTS components, attached with tape and enhanced contact with thermal paste

= Location of the thermal sensors on the mock up motor design. An additional thermal sensor is located on the conduction cylinder and one more on the cryocooler cold head
Data collection

- Current source supplied to thermal sensors
- Voltages read from thermal sensors
- Recorded and stored to give temperature data
Experimental Facilities

Experimental facilities used to validate thermal transient and steady state models

- Top plate
- Cryocooler
- Passive shield
- Mockup motor
- Cryostat

Recording Data
• Temperature Gradient in inductor, achieved SS in 10 hours
  – Pancake ~ 45-50 K
  – YBCO plates increase temperature from ~45K to <100K
  – Cold head temperature steady
Experimental Results – Heating YBCO Plates

- Steady state $T \sim 45–50 \text{ K}$
- YBCO plates temperature increased above 100K

Temperature gradient over 40K achieved
Experimental Results – Cooling YBCO Plates

- Pancake temperatures increase ~ 5K with pancake heaters activated
- YBCO heaters deactivated to allow cooldown
  - YBCO plates return to steady state temperature
  - Trapping Flux in E-M motor design

![Graph showing temperature over time during cooling process]

Stop YBCO Heaters

Pancake rise in temperature acceptable

YBCO cooldown ~1Hour
Experimental Results – Steady State Profile

• Final S.S. Temperatures
  1. Coldhead ~13K
  2. Bottom of Aluminum Cylinder ~ 38K
  3. Top Pancake ~ 52K
  4. Top YBCO Plate ~ 44K
  5. Middle Pancake ~ 50.1K
  6. Bottom YBCO Plate ~ 44K
  7. Bottom Pancake ~ 51.5 K

From (1) coldhead to (2) aluminum cylinder $\Delta T = 25K$

From (2) aluminum cylinder to (6) bottom YBCO plate $\Delta T = 8K$

From (2) aluminum cylinder to (7) bottom pancake $\Delta T = 13.5K$
Experimental Results – Apparatus Thermal Gradient

1. Coldhead
   - Modeling results (expected) 7 K
   - Experimental results 13 K

2. Bottom Aluminum Cylinder
   - Modeling results (expected) 20.5 K
   - Experimental results 38 K

6. Bottom YBCO plate
   - Modeling results (expected) 23.9 K
   - Experimental results 44 K

7. Bottom Pancake
   - Modeling results (expected) 21.9 K
   - Experimental results 51.5 K
Experimental Results – Apparatus Thermal Gradient

(1) Coldhead to (2) Aluminum Cylinder Bottom: $\Delta T = 25K$

– Expected results from simulations $\Delta T = 7.5K$
– Use of copper connector piece creates an impedance to heat flux
– Copper piece has some contact resistance in the connection

• Calculated temperature at top of Aluminum Cylinder = 34.5K
  (from thermal resistance of aluminum body)
  – (vs. expected results of 18.8K from simulations)
Experimental Results – Apparatus Thermal Gradient

(2) Aluminum cylinder to (7) Pancake: $\Delta T = 13.5K$ (measured) (expected from simulations $1.4K$)

- Assume no contact resistance and measured $\Delta T=13.5K$, $k_{\text{windings}} = 0.13 \text{ W/m-K}$
  - Very low value of $k$ (not realistic)
  - Simulations used 1.4 W/m-K
  - Literature values of $k$ range from 0.3 – 80 W/m-K

- Using measured $\Delta T = 13.5K$ and $k=1.4 \text{ W/m-K}$ (estimate, same as used in simulations), then the contact resistance = $22 \text{ K/W}$ (between pancakes and aluminum, high resistance but reasonable)
Conclusions

Cooldown and Steady-State (setback):

- Inductor Mockup required 11 hours to reach steady state, about twice what was expected from simulations
  - Connecting to cold head has higher contact resistance
  - Cryocooler power not as ideal curve
- Steady state Tmax ~50 K in Pancake and Plates, > 30K (simulated)
  - Higher contact resistances formed during construction
  - Better winding technique is needed

3-stage cooling for YBCO flux trapping (success):

- Temperature gradient > 40K achieved from YBCO plates to the BSCO pancakes (superconducting BSCO, normal YBCO)
- 3-stage cooling for flux trapping is feasible

- Overall proof of principle of the thermal aspects of the motor design was successful, better construction is needed for actual prototype