Design and Analysis of Cryogenic Cooling System for Superconducting Motor

Abhijit Khare
Rensselaer Polytechnic Institute
Troy, NY

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CHEETA
Center for High-Efficiency Electrical Technologies for Aircraft

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Overview

- Motivation
- Overview of the Superconducting Motor
- Cooling System concept and Analytical Design
- Cooling System representation in Modelica/Dymola
- Current and Future work

Our Team and Our Project

- CHEETA (Center for High-Efficiency Electric Technologies for Aircraft)
  - Established in 2019 under NASA ULI program
  - Bringing together world experts in Aeronautics, Electrical Systems and Material Science
  - Multi-Institutional team of Universities and Industry groups with Government research collaboration
  - Focused of developing technologies for hydrogen powered, fully electric commercial aircraft utilizing LH2 storage with Fuel Cell system
  - Use of H2 as a cryogenic cooling medium and as fuel
  - Increased power density motors

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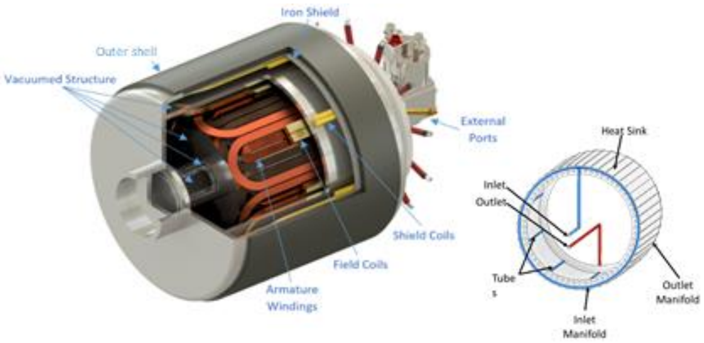
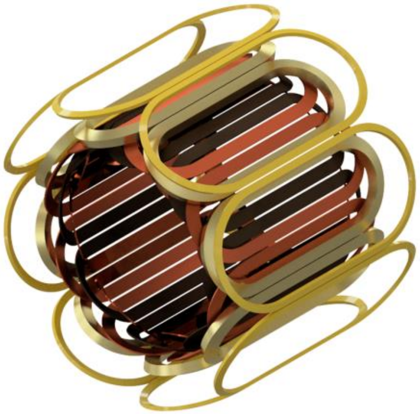
Superconducting Motor Overview

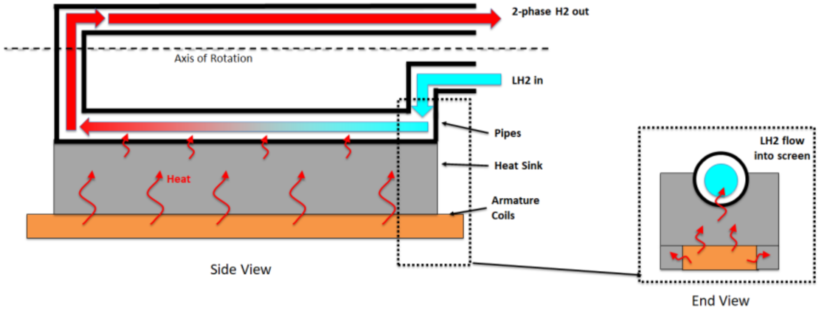
- Superconducting (SC) motors are electromechanical Alternating Current (AC) synchronous machines that use superconducting windings where conventional machines use copper coils
- Our design uses an outer-rotor design (armature coils are on the stator, and field coils are on the rotor)
- Magnetic field on the rotor is contained by “shield” coils
- Low AC loss MgB_2 superconducting coils are used with critical temperature of 39K
- There are significant AC losses in the armature windings (3000-4000 W) but extremely low losses in the field and “shield” windings (1-10 W)

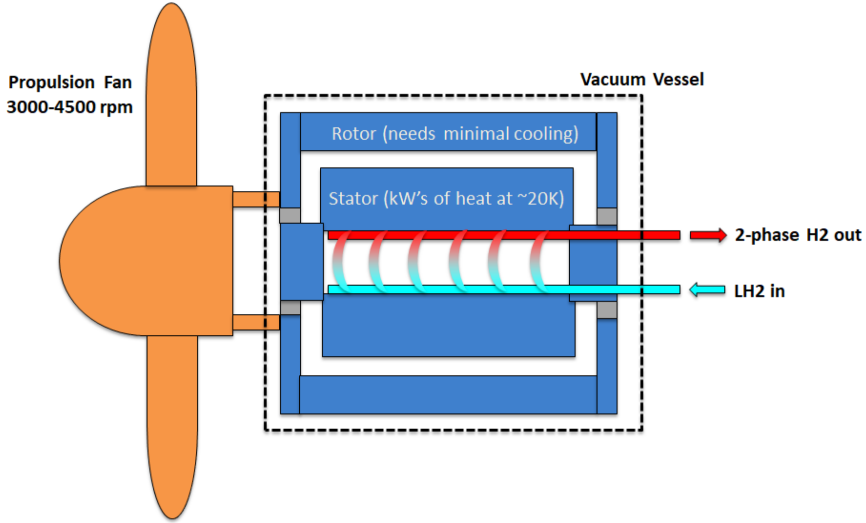




Armature Cooling Concept

- As mentioned stator is on the inside, and rotor is on the outside
- Single phase LH2 enters as a liquid, and exits as a 2-phase mixture H2 after absorbing heat from the stator (approximately 4kW)
- With 16 motors on the aircraft and approximately 1.66MW as the power of one motor, we get an available cooling budget of around 4.3kW per motor, and an LH2 boil-off rate per motor of 9.66 g/s, assuming 20-30% of available enthalpy of vaporization in fuel, available for motor cooling





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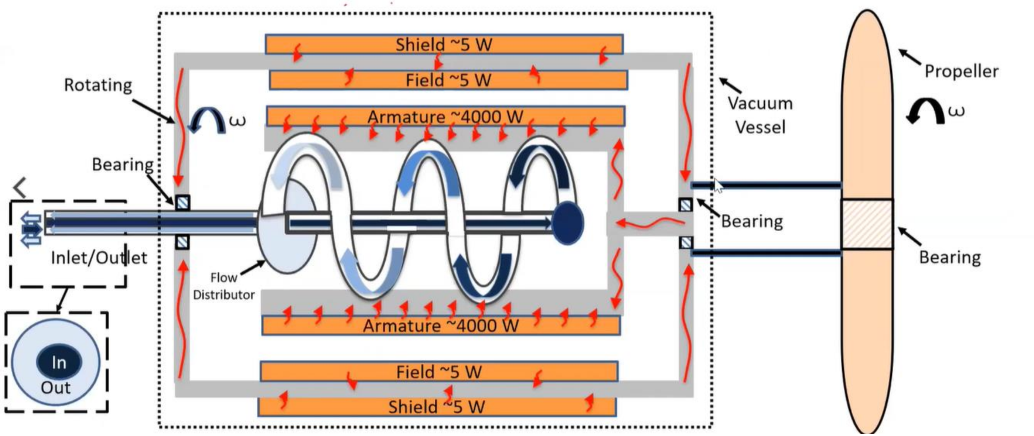
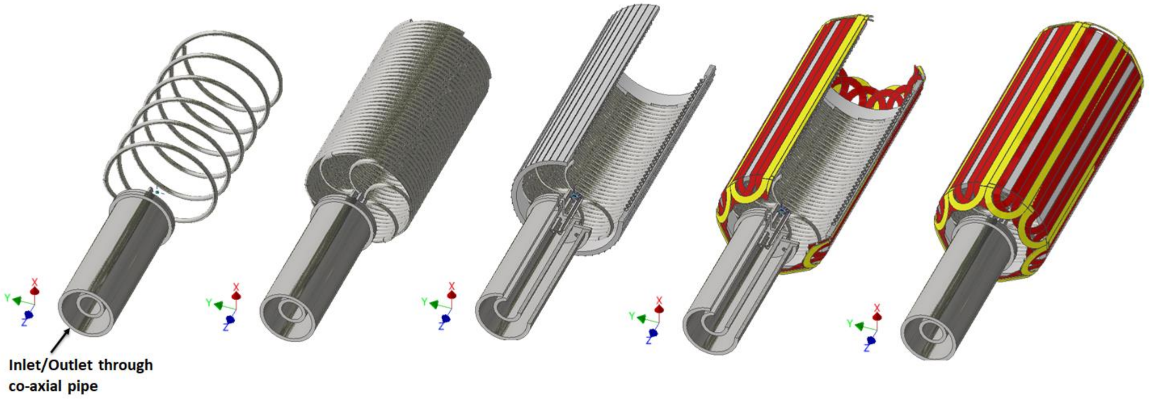
Cooling Design Concept

- Concentric pipe for inlet and outlet coolant
- The inlet LH2 goes to the end of the assembly, and then “returns” towards the start by way of helical coils
- The armature heat is absorbed by the coolant via the Aluminum heat sink, changing phase to 2-phase H2 in the process
- Heat from field and shield coils is conducted through an Aluminum structure and the bearings/rotary conduction cooling scheme to the H2.
- Entire structure is in a vacuum vessel





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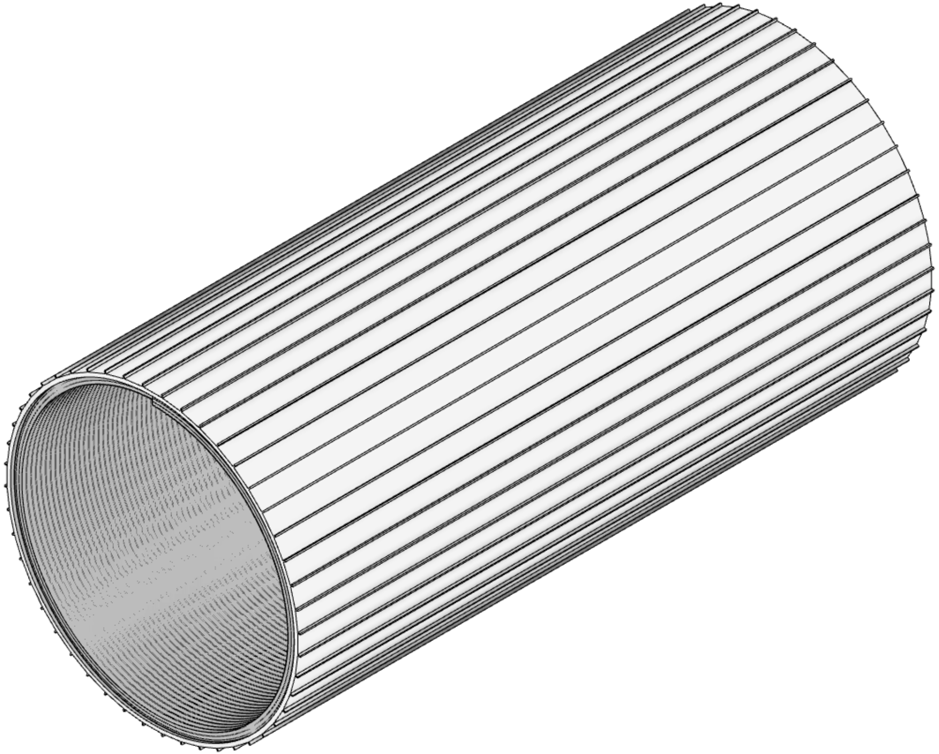
Flow Through Helical Tubes

- Centrifugal forces cause secondary flows circulating outward into the core region of the pipe to form a pair of symmetrical vortices.
- The main and secondary flows together create a flow pattern in which the maximum velocity is shifts outward from the center of the tube
- Secondary flow produces a transverse transport of the coolant over the cross section of the tube
- This improves heat transfer capability but increases pressure drop compared to a straight pipe



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Heat Transfer in Helical Tubes

- Critical Reynolds number for flow through helical tubes, assuming Re_{crit} is 2300, if given by

$$Re_{crit} = 2300\left[1 + 8.6\left(\frac{d}{D}\right)^{0.45}\right]$$

- Considering the effect of pressure drop through friction factor ζ

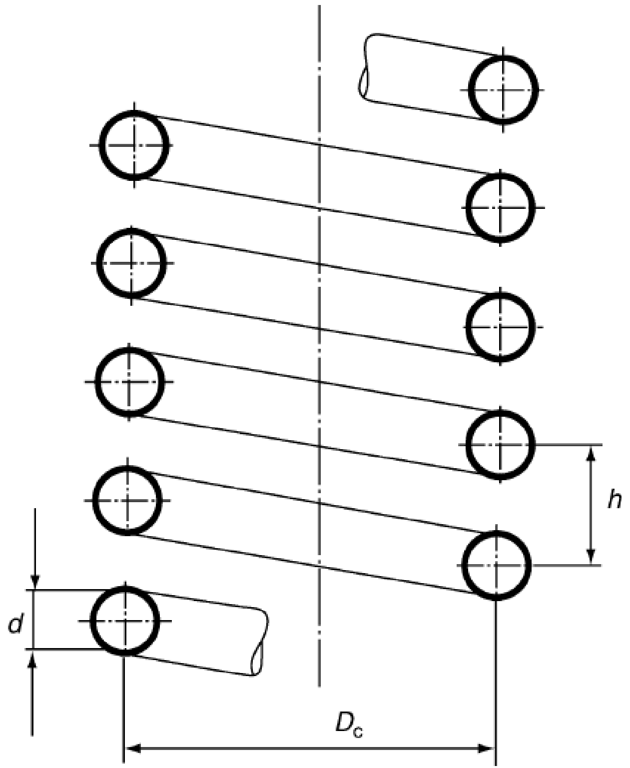
$$\zeta = 0.3164Re^{-0.25} + 0.03\left(\frac{d}{D}\right)^{0.5}$$

- Nusselt number is calculated as:

$$Nu = \frac{\left(\frac{\zeta}{8}\right) Re\ Pr}{1 + 12.7\left(\frac{\zeta}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)}$$

- Calculating Re to be greater than critical, therefore giving us turbulent flow, the mean convective heat transfer coefficient is calculated as:

$$\alpha = \frac{Nu\ \lambda}{d}$$



Pressure Drop in Helical Tubes

- The pressure drop is calculated by breaking down the tube into a series of “bends”
- Assuming turbulent flow through the Re calculation, the local pressure loss coefficient is given by

$$dP = \zeta \left(\frac{\rho}{2}\right) Vel^2$$

Where ρ is the density of fluid, Vel is the velocity of fluid flow which can be calculated through the mass flow rate, and the friction coefficient ζ is calculated as:

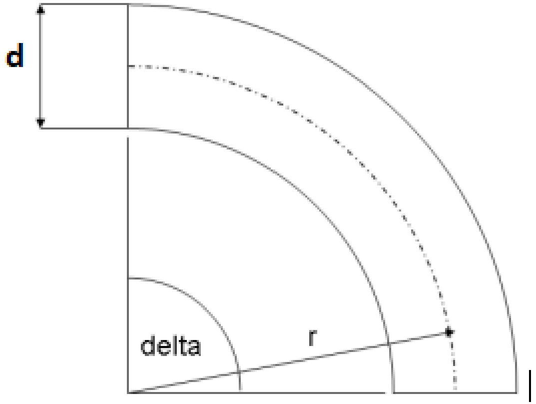
$$\zeta = k_{Re} A1\ B1\ C1$$

where, $k_{Re} = 1 + \frac{4400}{Re}$ for 0.50 < r/d < 0.55

$k_{Re} = 5.45\ Re^{0.118}$ for 0.55 ≤ r/d < 0.70

$k_{Re} = \frac{11.5}{Re^{0.19}}$ for 0.70 ≤ r/d < 3.00 where r = D/2

A1, B1 and C1 are coefficients considering angle of turning, relative curvature radius and coefficient considering effect of elongation on cross section



d/D	0.2	0.14	0.098	0.069	0.049	0.024	0.012
l/d	231	165	365	205	477	579	636
n	15.5	8.9	11.5	5	7.5	4.5	2.5

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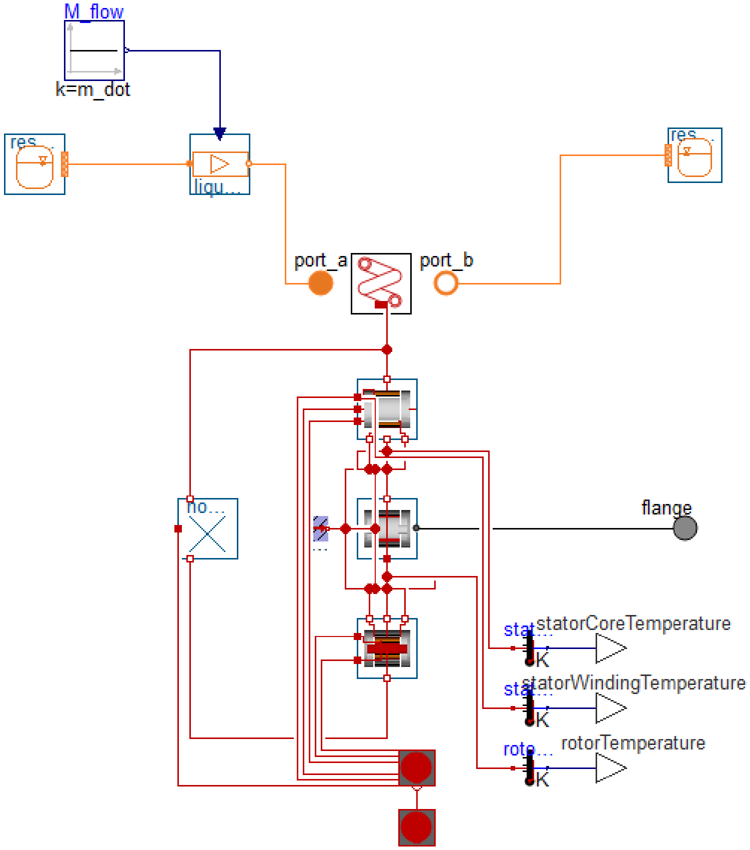
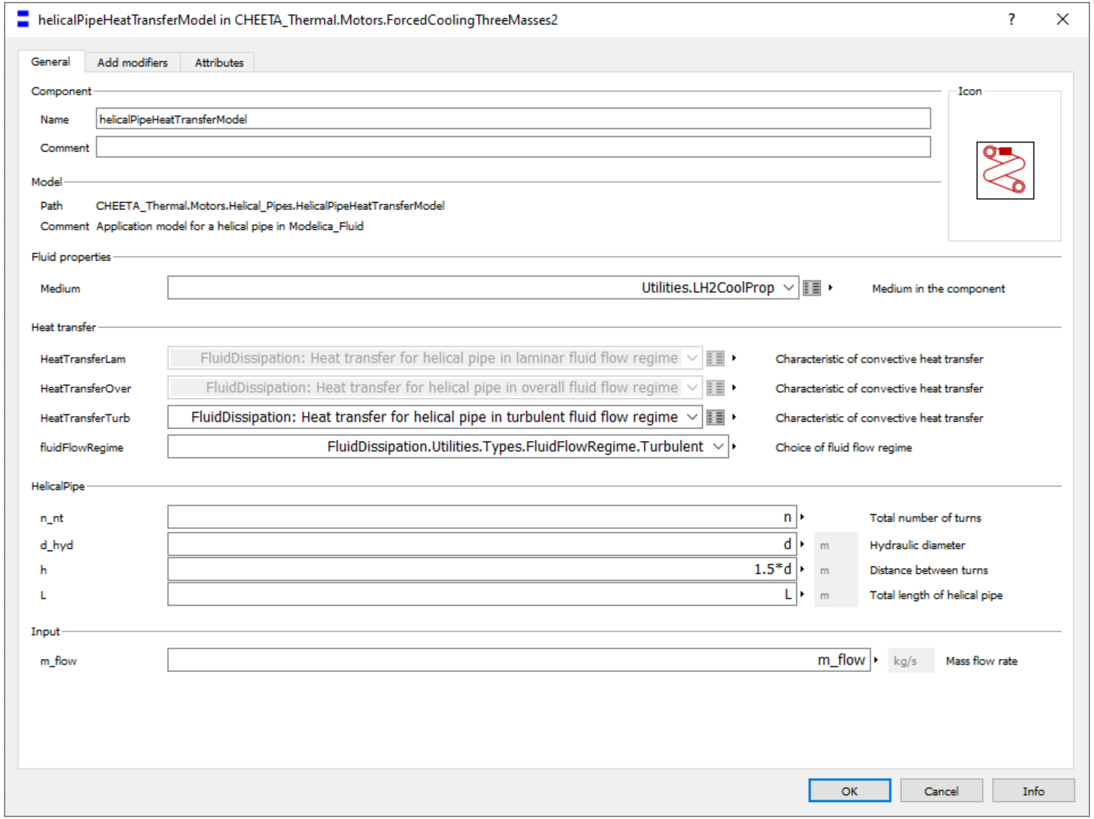
Mathematical Model

- Outer Rotor AC Synchronous motor model, including thermal parameters, customized for superconducting MgB_2 coils
- Helical Tube model considering turbulent flow, customized to match dimensions of the tubes used, heat transfer properties and pressure drop model
- H2 media model allowing phase change from LH2 to 2-phase H2, circulated through the helical tubes by a fluid pump, set to operate at a defined mass flow rate



Parameterization of the Model

- Setting the coolant medium as a CoolProp property based LH2 model (LH2 is not a pre-programmed medium available)
- Setting the heat transfer regime as turbulent based on calculation of Reynolds Number Re to be above critical
- Setting the pressure drop fluid flow model to be turbulent for proper selection of k_{Re}
- Parameterizing the dimensions for the tube model as externally changeable, along with the mass flow rate



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Current Work and Future Steps

- Current work includes simulating the model to analyze the heat transfer performance so as to siphon off 4.3kW of heat rejected by the SC motor
- Current work also includes analyzing pressure drop values to be able to predict if a particular mass flow rate would be enough to achieve the required heat transfer
- An inverter model is also being developed to simulate with the motor, and test cases are being prepared for Battery-HTS Cables-Motor-Inverter case and Fuel Cell-HTS Cables-Motor-Inverter case
- Future work involves testing for a case involving hybrid operation between two prime movers (Fuel Cell and Battery, both supplying power to the motor without voltage overload)
- Once the thermal model integration is completed, the next steps involve integrating it with the electrical model, and running system level test cases

Acknowledgements

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