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LMQFXA Flow Rate and Heat Transfer

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Abstract

The LMQXFA cold masses are quadrupole, superconducting magnets that function at 1.9 K that are slated to be used as upgrades for the High Luminosity LHC. To reach operating temperature, chilled gas and eventually liquid helium flows through the magnets' vents. If the cold mass is cooled too quickly, thermal contractions could damage internal components. The goal of this project was to create mathematical models for the flow rate and heat transfer in the magnets to 4.5 K, the temperature of liquid helium, using Engineering Equation Solver (EES). The models will help estimate the rate at which operators can safely cool the magnets.

An incomplete LMQFXA on Stand 4 in Industrial Building 1

Introduction

As one of the contributors to the High Luminosity Large Hadron Collider(HL-LHC), Fermilab is tasked with delivering upgrade magnets to CERN in Geneva, Switzerland as part of the U.S. HL-LHC Accelerator Upgrade Project. The LHC is the world's largest particle accelerator, colliding protons at high energies to discover new subatomic particles. The goal of the High Luminosity project is to increase the collision rate by a factor of 10, which will improve the accuracy measurements of rare particles[1]. Fermilab will be providing LMQXFA cold masses, which are quadrupole magnets that are used to focus particle beams. The magnets consist of an exterior stainless steel shell containing two magnets made of an outer aluminum shell, iron yokes, and niobium$_3$ tin coils. They are used in particle accelerators like focusing lenses with light. The four magnetic fields repel the particle beam, keeping it centered. The magnetic field created by the cold masses are 11 Tesla. For reference, the field created by a refrigerator magnet is about 0.01 Tesla. At low enough temperatures, they become superconductive or, in other words, drastically reduce their resistance, allowing more electricity to flow.

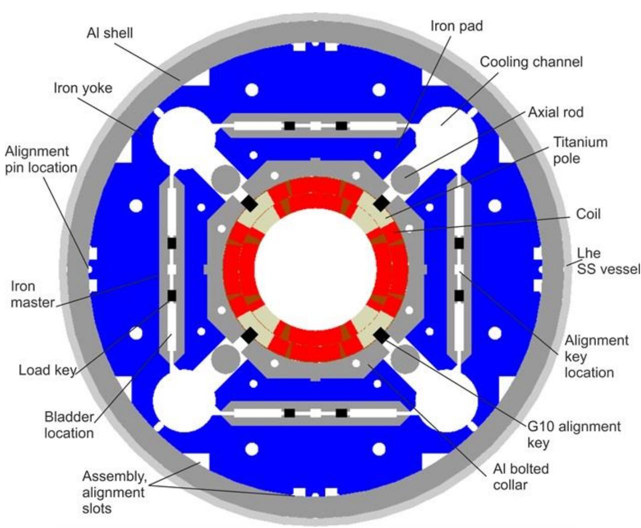

Figure 1: A cross section of the cold mass, labeling all the components.

This project is centered around multiple systems of equations involving the thermophysical properties of helium and the metals of the cold mass. Engineering Equation Solver (EES) was the ideal program for problem because of its functions for calculating thermodynamic values and ability to solve systems with thousands of equations. For this project, there will be sets of equations for fluid mechanics, heat transfer, and heat transfer with finite element analysis. For the fluid mechanics portion, the goal is to find the flow rate, in kilograms per second, of the of the helium through the magnet. Helium flows through three different openings, being the cooling channels, the bladder locations, and the larger assembly alignment slots near the cooling channels as depicted by figure 1. In this project, the cooling channel, bladder locations, and assembly alignment slots were dubbed key holes, shim slots, and vents, respectively. Finite element analysis (FEM) is an analytical technique used in solving for properties of objects. The object in question is divided into regular shapes called elements. On each of the elements is at least one node. The location of the nodes in relation to one another are used in the equations to solve for variables like internal stress or, in this case, heat transfer.

Methods

For the first flow rate model, the cold mass was assumed to be one continuous pipe with a helium flowrate of 20g/s. For simplicity, the key holes were assumed to be perfectly circular and the shim slots were assumed to be isolated rectangles. With the pressure drop across the system staying constant, a system of equations was established based on turbulent flow though pipes. For the second flow rate model, the cold mass was depicted as a system with two sudden expansions and two sudden contractions as helium entered and exited the vents of each magnet. The equations were adjusted to account for minor losses of energy due to said expansions and contractions, then solved.

$$\rho \cdot \left(A_v \cdot V_{v,1} + A_s \cdot V_{s,1} + A_k \cdot V_{k,1}\right) = \dot{m}_t$$

$$\left[l \cdot \frac{f_{v,1}}{2 \cdot D_v} + \frac{K_{vc}}{2}\right] \cdot V_{v,1}^{2} = \left[l \cdot \frac{f_{s,1}}{2 \cdot D_s} + \frac{K_{sc}}{2}\right] \cdot V_{s,1}^{2}$$

$$\left[l \cdot \frac{f_{s,1}}{2 \cdot D_s} + \frac{K_{sc}}{2}\right] \cdot V_{s,1}^{2} = \left[l \cdot \frac{f_{k,1}}{2 \cdot D_k} + \frac{K_{kc}}{2}\right] \cdot V_{k,1}^{2}$$

This set is an example from the second flow rate trial. The first equation connects the unknown velocities to the total mass flow rate. The second and third equations are the equations for the pressure drop for the openings set equal. The output velocities were then converted to mass flow rates.

For the first trial of the heat transfer portion of the project, the cold mass was assumed to be one solid object and heat only transferred one dimensionally. A system of equations was then derived and solved. The cold mass was divided in to twelve equal sections for the second attempt and heat transfer was again one-dimensional. The helium was assumed to enter the magnet at 200 K, but as it passed through the cold mass, it was warmed. The change of helium temperatures across the twelve sections was included in a new system of equations. Solutions recorded onto a generated table, varying with the progression of time. Two-dimensional heat transfer was accounted for in the final revision of the program using FEM. The twelve sections were assumed to be isolated and the magnet was sectioned into symmetric slices every 45^o. Nodes were assigned to the different materials so that each element consisted of only one type of metal. Because the cross section of the magnet is circular, the most effective coordinate system for FEM is cylindrical, making the elements portions of rings. The energy balance equations were written with energy transferred in from the surroundings set equal to the current energy stored within the element for each node and the results were again recorded onto a time table.

Results

The predictions most of the date make are accurate to expectations, but, without the LMQFXA cold mass operational, there is no way to validate the outputs. From the flow rate equations, the expected average flow rates through the key holes is around 0.01823 kg/s, 0.001097 kg/s through the shim slots, and 1.516E-5 kg/s through the vents

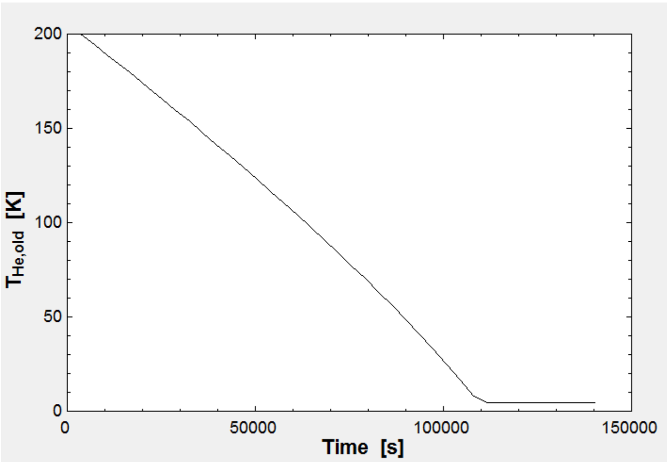

Figure 2: First trial of heat transfer, plotting helium temperature against time

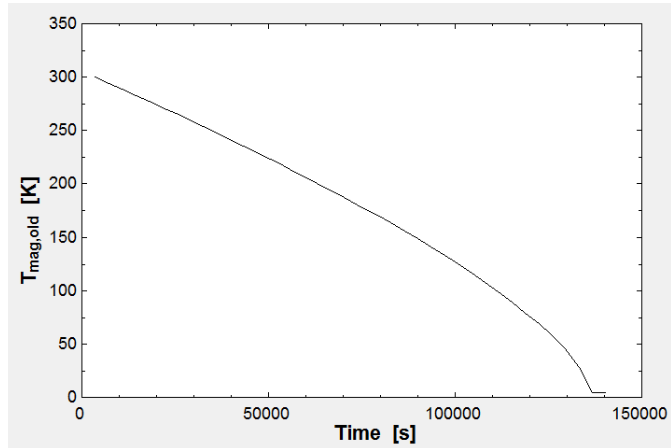

Figure 3: First trial of heat transfer, plotting the magnet temperature against time

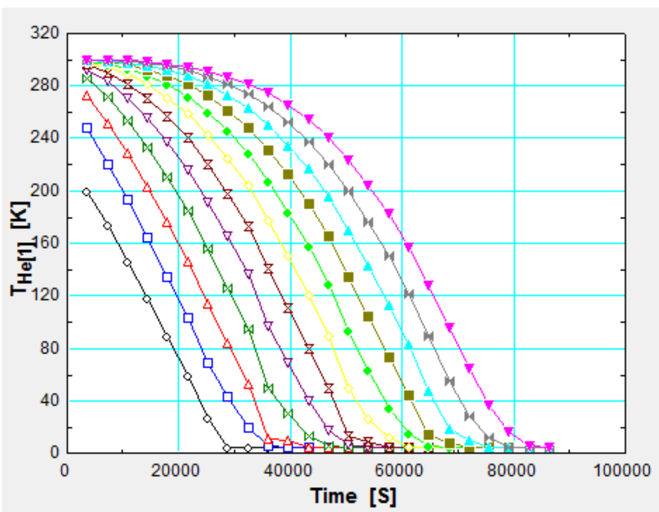

Figure 4: Second trial of heat transfer, plotting helium temperature against time

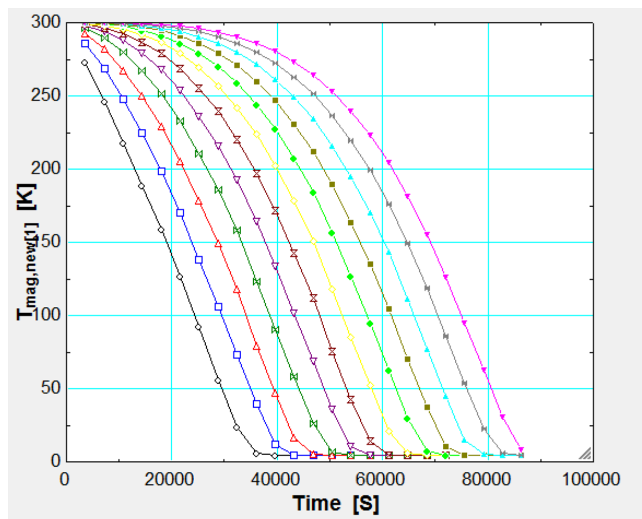

Figure 5: Second trial of heat transfer, plotting the magnet temperature against time

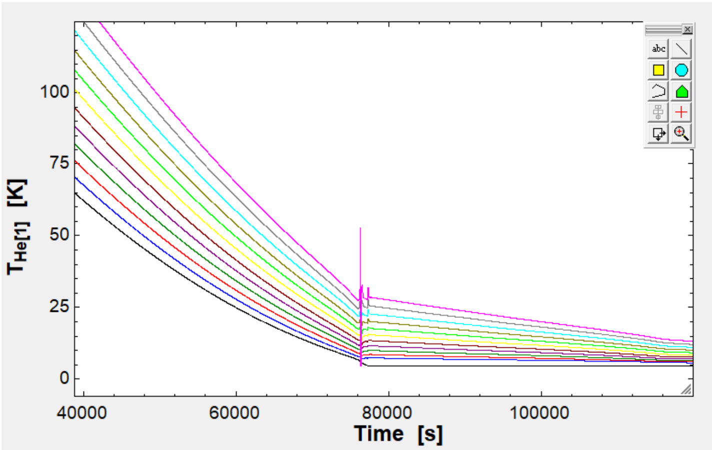

Figure 6: Third trial of heat transfer, plotting helium temperature against time

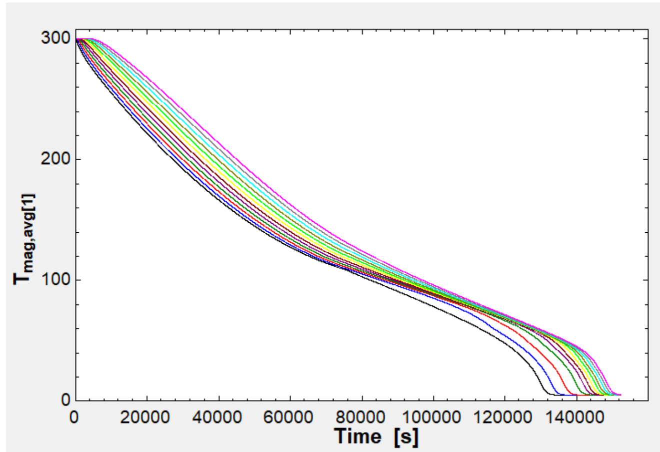

Figure 7: Third trial of heat transfer, plotting the average magnet temperature against time

Conclusion

These programs were not designed to be a precise measurement of the magnet's helium systems. As previously stated, they mostly fall in line with what was expected, but there is no way support that conclusion. The final heat transfer program does have some odd problems. Because the node equations were based on predefined time steps, the equations become unstable and the values fluctuate up and down after so many iterations. The program fails if the time step is increased beyond 10 second intervals. Secondly, the graph of the helium temperature vs time has a large spike around 7500 seconds that does not exist within the data

If this project were to continue, the first step would be to form a more in depth analysis of the flow rates. The programs described assumed the key holes to be simple geometric shapes, when they are not. The biggest improvement for the heat transfer would be to find a way around the small time step in the final heat transfer trial. Currently the program runs over fifteen thousand times and takes upwards of 2 hours to complete. The next step for these models would be a thermal stress analysis to see if any of the internal components would be damaged.

Acknowledgements

This project would not have been possible without the guidance of Roger Rabehl. He helped me learn fluid dynamics and heat transfer, classes I will not be taking until this coming year. Antonios Vouris also helped by providing me with the magnet’s measurements which were central to this project.

References

1. "CERN Accelerating science." The HL-LHC project | The HL-LHC Project. N.p., 22 Feb. 2016. Web. 03 Aug. 2017.