Design and Optimization of a Solenoid for Magnetic Field Treatment Using Finite Element Analysis

Sean Francis[1] and Soojin Jun[2]

1 Bioengineering, Department of Molecular

Biosciences and Bioengineering, College of Tropical Agriculture and Human Resources,

2 Department of Human Nutrition, Food and Animal Sciences

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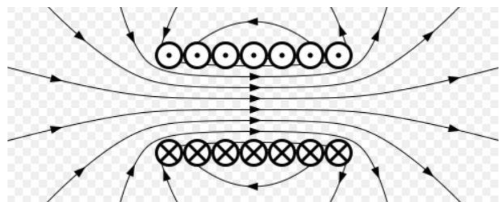
ABSTRACT

Electromagnetic fields of 15 mT are part of a proprietary treatment to prevent freezing in beef samples at -4 °C. Former studies using Monte Carlo computer simulations have shown fields ranging from 100-200 mT alter the radial distribution function and change the internal energy up to ± 0.1 E/kJ (mol^{-1}). Modeling and simulating of electromagnets provides valuable information regarding field strength as well as heat production for use in optimization. Initial calculations using Maxwell's equations were used to extrapolate coil parameters before a novel design was modeled in Solidworks. "Electromagnetics Simulation Software" (EMS) provided accurate finite element analysis in both dynamic and steady state conditions for magnetic field simulation and temperature respectively.

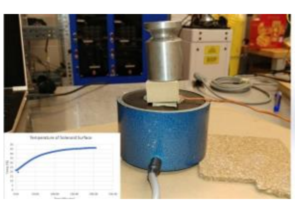
INTRODUCTION

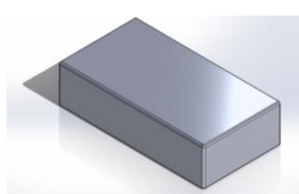


James Maxwell first derived equations relating the integrated magnetic field around a closed loop to the electrical current passing through the loop in his 1861 paper “On the Physical Lines of Force”. The basis of which all other electromagnetic equations are based/interchangeable with. One such equation is Ampere’s circuital law and its derivation which was used to extrapolate the optimal coil parameters within the constraints of our system. The coil parameters were further experimented with after the finite element analysis software was tested for accuracy and consistency.

Magnetic field simulation results were compared to measurements from a “3B Scientific U21901 Helmholtz Coil” using a “Frederiksen 4060.5 Teslameter”. Magnetic flux was ~4-5 mT using the Teslameter while simulation results were 5.12-6.14 mT; a .12-1.14 difference. Coil parameters and dimensions were kept identical as per the specification sheet for the Helmholtz Coil. This included 5 A power inputs, 100 turns, 32 gauge wire and 5.72 cm coil gap.

Further testing included steady state temperature accuracy using a fixed core solenoid. A dial caliper was used to measure the dimensions of the solenoid and power input was 60V at 280 mA. Temperature was 21.6 °C ambient and the steady state temperature was 46 °C for the device. Power input for the simulation was 60V and the convection coefficient was 14 W/m²K. Steady state temperature in the simulation was 44.9 °C, 1.1°C less than the recorded results.





Additionally, simulations of existing electromagnet setups indicated that solenoid core extensions currently in use were fully saturated and not conveying the B-field we had initially thought. After adding more material to the core in the simulation, the B-field increased substantially. Implementation of thicker cores extensions and subsequent measurement with the Tesla meter proved that previous core extension were indeed too thin. Note: Images of the device are confidential and not posted here.

MATERIALS & METHODS

Equations and Derivations

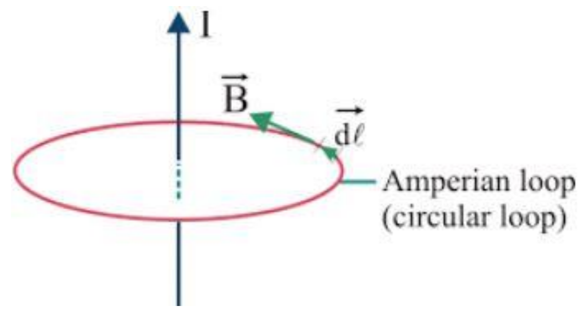
Based on Ampere's Law for a wire of infinite length, where $\sum B_{||}\Delta l$ is the sum of all the magnetic fields (B) parallel (| |) to some length (Δl). This equivalent to the permittivity of free space (μ_0) multiplied by the current (I).

$$\sum B_{||}\Delta l = \mu_0 I$$

Integration leaves us with:

$$\int B\Delta l = \int Bdl = B\int dl = \mu_0 i \rightarrow \; B = \frac{\mu_0 i}{2\pi r}$$

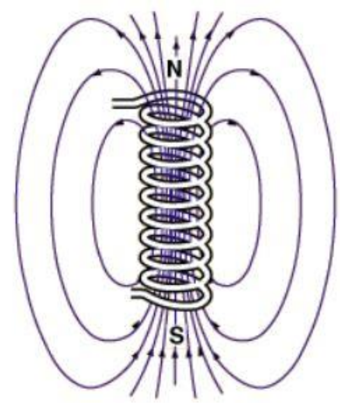
B=μH → H=i/2πr



For an ideal solenoid with N number of turns in free space:

$$B = N\frac{\mu_0 i}{2\pi r}$$

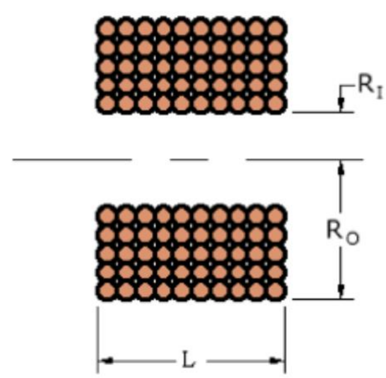
For a solenoid with a solid core, $B = kN\frac{\mu_0 i}{2\pi r}$ where $k = \frac{\mu}{\mu_0}$



Resistance in the coil is important and a simple change of wire gauge can significantly affect how much resistance there is.

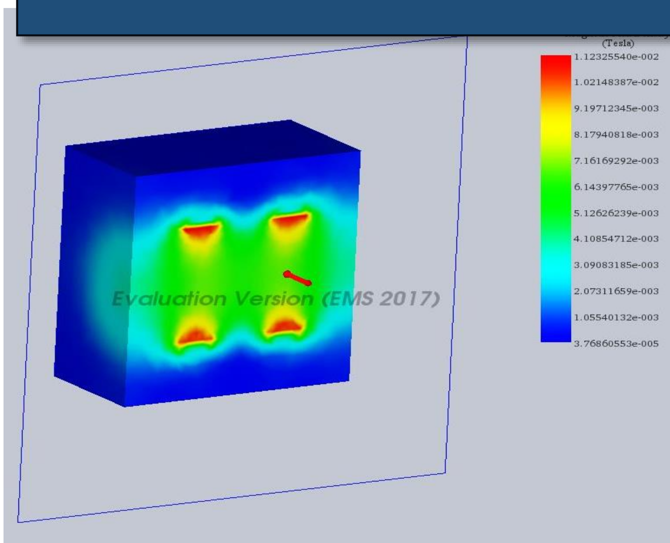
Resistance, R_C is: $R_C = \frac{4\rho({R_0}^2 - {R_I}^2)L}{\emptyset^4}$, where ρ is the wire resistivity, R is the radius outer and inner respectively, L is the coil length and ∅ is the wire diameter.

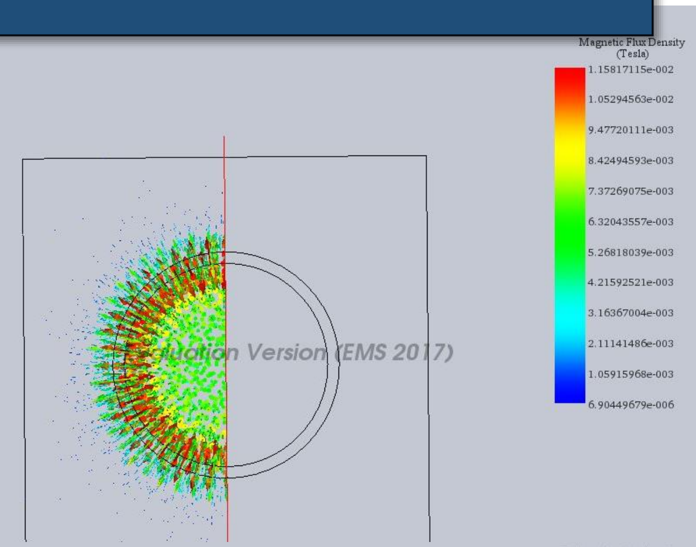
The magnetic field at the center of the solenoid, H_0 can be shown given any length L, and inner Radius, R_I allowing us to vary the outer radius and wire diameter for optimal field strength



$$H_0 = \frac{NI(\frac{L}{2R_i}\left[\operatorname{arcsinh}\left(\frac{\frac{R_0}{R_i}}{\frac{L}{2R_i}}\right) - \operatorname{arcsinh}\left(\frac{2R_i}{L}\right)\right])}{2(\frac{L}{2R_i})R_i(\frac{R_0}{R_i} - 1)}$$

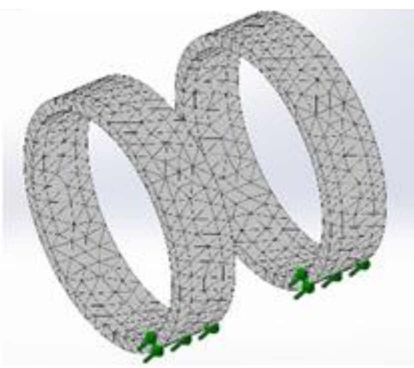
RESULTS

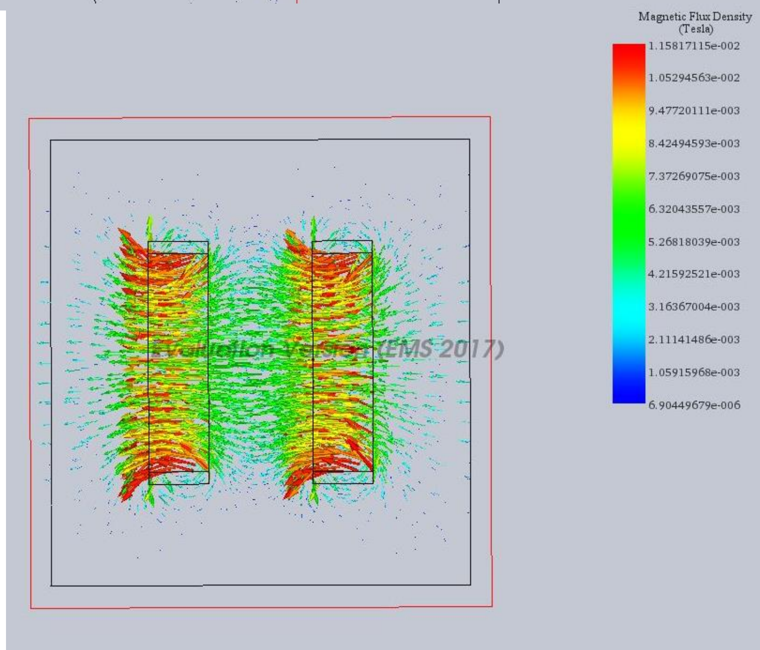


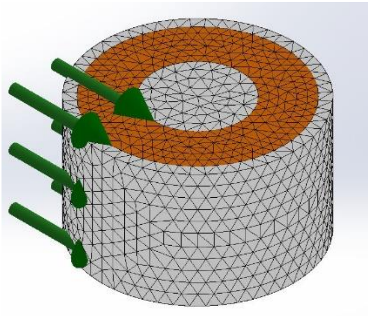


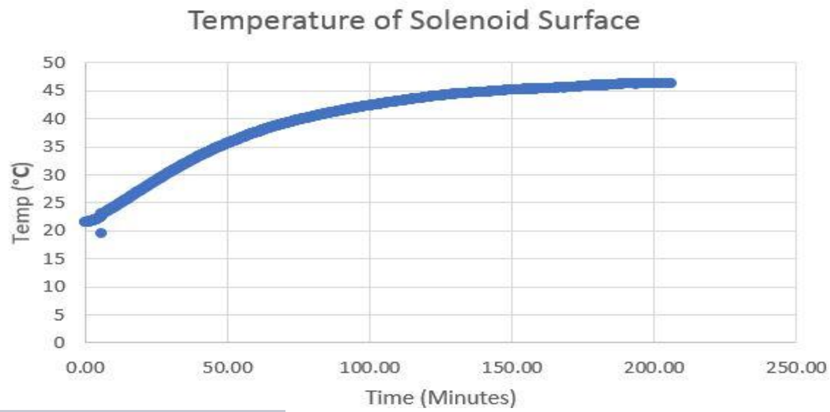
From Above Clockwise:

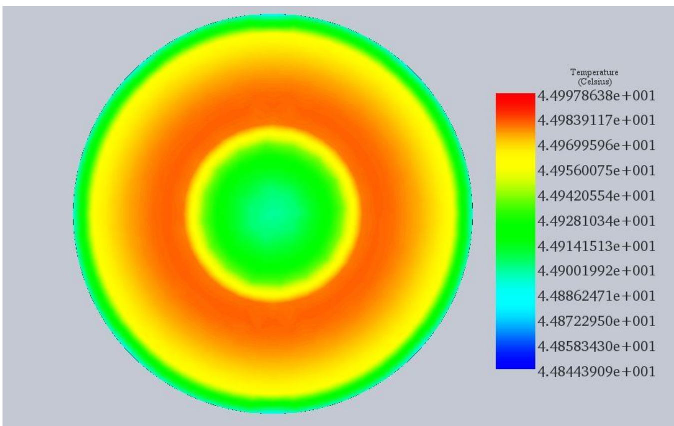
- **Magnetic Flux Density of the Helmholtz coil isometric view**
- **Frontal view of flux vectors**
- **Side view of flux vectors.**





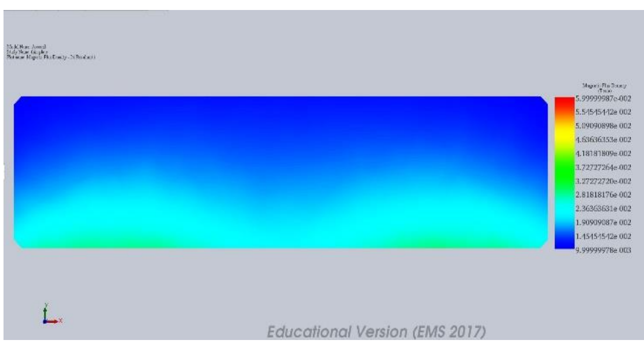


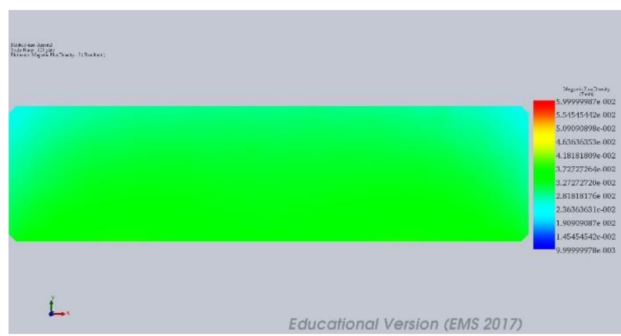




Clockwise from left:

- **Top view of the steady state temperature in the solenoid**
- **Solenoid mesh with arrows indicating electrical current direction**
- **Temperature vs Time of the actual device**





Comparison of field distribution between thin plate (left), and (thick) used to extend the solenoid core into our desired experimentation chamber.

(Please note the device itself isn't shown because it is proprietary.)

CONCLUSION

Empirical formulas were investigated but not extrapolated for optimal solenoid starting parameters given certain initial conditions. FEA software was vetted and proven to be accurate in simulation of steady state temperature to within 1.1 °C and magnetic flux variance of 1.14 mT. It also proved useful in modeling current systems which were underperforming, and subsequently upgraded based on findings from the experimentation of the model within the EMS software.

Future Research

Future research will include complete derivations and empirical formulas for optimal starting parameters for the type of solenoid proprietary to the magnetic field treatments used in super cooling research.

REFERENCES

- Dolotenko, Mikhail I., et al. Strong and Superstrong Pulsed Magnetic Fields Generation, De Gruyter, Inc., 2014. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/uhm/detail.action?docID=893512.
- Marques, E., & Mendes, A. (2017). Modelization and optimization of solenoid magnetic structures for IPT systems. Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), 2017 11th IEEE International Conference on, 489-494.
- Paul, James. "Coilgun Systems." Coilgun Systems, 2001, www.coilgun.eclipse.co.uk/.
- Magnetic and Electric Field Simulation. (n.d.). Retrieved April 06, 2018, from https://www.emworks.com/product/EMS

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