L3b: Coil Design and Temperature Calculations

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Why

So far in this course we have only modelled a coil as a rectangle.

In reality we need to design a coil with multiple turns.

The coil design needs to:

- Create the desired electromagnetic force
- Match the voltage of the power supply
- Not exceed the maximum temperature rise

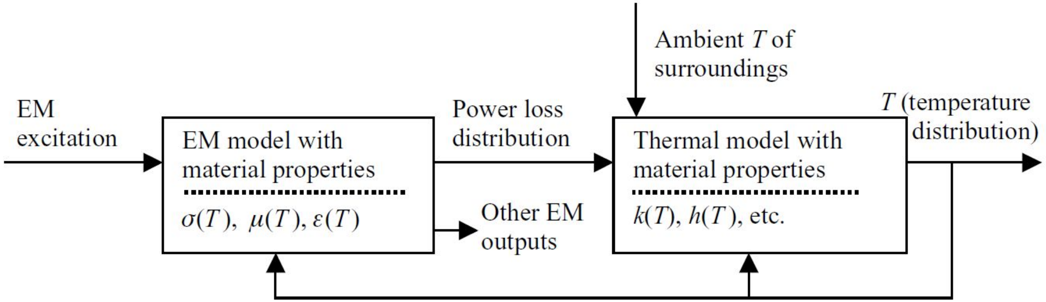


FIGURE 12.1 Modeling temperature and its effects in magnetic devices, to be discussed in this chapter.

Wire Size Determination for DC Currents

Why - Wire Size Determination for DC Currents

DC is a good place to start!

How - Wire Size Determination for DC Currents

DC current is determined by Ohm's law

$$I = V/R \quad (12.1)$$

Resistance is defined by the length, conductivity and cross sectional area.

$$R = l/(\sigma S_c) \quad (12.2)$$

For a circular conductor:

$$S_c = \pi r^2 = \pi d^2/4 \quad (12.4)$$

Conductivity is affected by temperature

$$\sigma = \frac{5.8\text{E}7\ \text{S/m}}{1 + 0.00393(T - 20^\circ\text{C})} \quad (12.3)$$

Commercially available circular wire sizes

$$d = (0.00826)(1.123^{-\mathrm{AWG}})\ \mathrm{m}\ (12.5)$$

AWG SIZE	NEMA Nominal Diameter (Inches)	NEMA Nominal Diameter (mm)	IEC R-20 Series (mm)
4/0	0.46	11.684	-
3/0	0.4096	10.404	-
2/0	0.3648	9.266	-
1/0	0.3249	8.252	-
1	0.2893	7.348	-
2	0.2576	6.543	-
3	0.2294	5.827	-
4	0.2043	5.189	5
5	0.1819	4.62	4.5
6	0.162	4.115	4
7	0.1443	3.665	3.55
8	0.1285	3.264	3.15
9	0.1144	2.906	2.8
10	0.1019	2.588	2.5
11	0.0907	2.304	2.24

AWG SIZE	NEMA Nominal Diameter (Inches)	NEMA Nominal Diameter (mm)	IEC R-20 Series (mm)
12	0.0808	2.052	2
13	0.072	1.829	1.8
14	0.0641	1.628	1.6
15	0.0571	1.45	1.4
16	0.0508	1.29	1.25
17	0.0453	1.151	1.12
18	0.0403	1.024	1
19	0.0359	0.912	0.9
20	0.032	0.813	0.8
21	0.0285	0.724	0.71
22	0.0253	0.643	0.63
23	0.0226	0.574	0.56
24	0.0201	0.511	0.5
25	0.0179	0.455	0.45
26	0.0159	0.404	0.4

AWG SIZE	NEMA Nominal Diameter (Inches)	NEMA Nominal Diameter (mm)	IEC R-20 Series (mm)
27	0.0142	0.361	0.355
28	0.0126	0.32	0.315
29	0.0113	0.287	0.28
30	0.01	0.254	0.25
31	0.0089	0.226	0.224
32	0.008	0.203	0.2
33	0.0071	0.18	0.18
34	0.0063	0.16	0.16
35	0.0056	0.142	0.14
36	0.005	0.127	0.125
37	0.0045	0.114	0.112
38	0.004	0.102	0.1
39	0.0035	0.089	0.09
40	0.0031	0.079	0.08
41	0.0028	0.071	0.071

AWG SIZE	NEMA Nominal Diameter (Inches)	NEMA Nominal Diameter (mm)	IEC R-20 Series (mm)
42	0.0025	0.064	0.063
43	0.0022	0.056	0.056
44	0.002	0.051	0.05
45	0.00176	0.0447	0.045
46	0.00157	0.0399	0.04
47	0.0014	0.0356	0.035
48	0.00124	0.0315	0.031
49	0.00111	0.0282	0.028
50	0.00099	0.0251	0.025
51	0.00088	0.0224	0.022
52	0.00078	0.0198	0.02
53	0.0007	0.0178	0.0187
54	0.00062	0.0157	0.0157
55	0.00055	0.014	0.014
56	0.00049	0.0124	0.0124

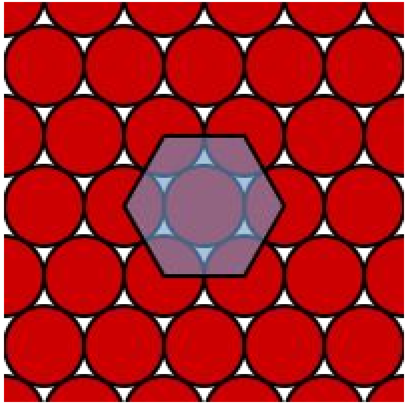
Adapted from data: http://www.litz-wire.com/wirediminsions.php

Theoretical packing

The relationship between the conductor cross sectional area and the available area is the ***Packing Factor***

$$F_p = NS_c / S_w \quad (12.6)$$

Maximum theoretical circle packing 91%



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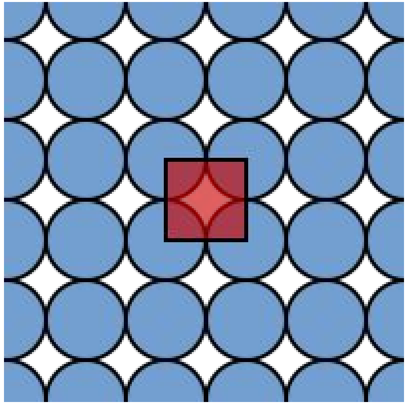

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Practical packing

Wire enamel

Bobbin or insulator

Nesting or not

Wire insulation

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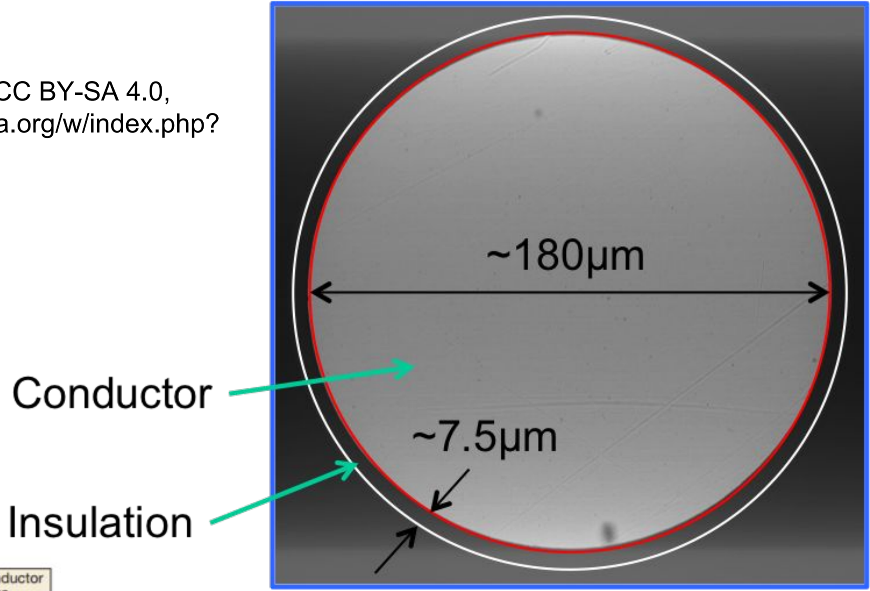

Dimensional table of magnet wire

The dimensional tables of magnet wire are as shown in Tables 12 to 18.

Table 12: Diamensional table of enamelled wire

Conductor			Class 0			Class 1			Class 2			Maximum conductor resistance 20℃ (Ω/km)	
Diameter (mm)	Tolerance (mm) Class 0, 1	Tolerance (mm) Class 2	Minimum film thickness (mm)	Maximum overall diameter (mm)	Estimated mass (kg/km)	Minimum film thickness (mm)	Maximum overall diameter (mm)	Estimated mass (kg/km)	Minimum film thickness (mm)	Maximum overall diameter (mm)	Estimated mass (kg/km)	Class 0, 1	Class 2
3.20	±0.04	–	0.049	3.388	72.4	0.034	3.338	72.2	–	–	–	2.198	–
3.00	±0.03	–	0.049	3.178	63.7	0.034	3.128	63.4	–	–	–	2.489	–
2.90	±0.03	–	0.049	3.078	59.5	0.034	3.028	59.3	–	–	–	2.665	–
2.80	±0.03	–	0.049	2.978	55.5	0.034	2.928	55.3	–	–	–	2.861	–
2.70	±0.03	–	0.049	2.878	51.7	0.034	2.828	51.4	–	–	–	3.079	–
2.60	±0.03	–	0.049	2.778	47.9	0.034	2.728	47.7	–	–	–	3.324	–
2.50	±0.03	–	0.049	2.678	44.3	0.034	2.628	44.1	–	–	–	3.598	–
2.40	±0.03	–	0.048	2.574	40.9	0.033	2.526	40.7	–	–	–	3.908	–
2.30	±0.03	–	0.046	2.468	37.6	0.032	2.422	37.4	–	–	–	4.260	–
2.20	±0.03	–	0.046	2.368	34.4	0.032	2.322	34.2	–	–	–	4.662	–
2.10	±0.03	–	0.045	2.266	31.3	0.031	2.220	31.2	–	–	–	5.123	–
2.00	±0.03	–	0.044	2.162	28.4	0.030	2.118	28.3	–	–	–	5.656	–
1.90	±0.03	–	0.044	2.062	25.7	0.030	2.018	25.6	–	–	–	6.278	–
1.80	±0.03	–	0.042	1.956	23.1	0.029	1.914	22.9	–	–	–	7.007	–
1.70	±0.03	–	0.042	1.856	20.6	0.029	1.814	20.5	–	–	–	7.871	–

https://www.hitachi-metals.co.jp/e/products/auto/el/pdf/MagnetWire_en.pdf

Example 12.1

Example 12.1 Simple DC Coil Design at a Given Temperature An axisymmetric copper coil is to be designed to operate at a maximum temperature of 60°C. The available winding area S_w is 1.E−3 m^2 and the average coil radius is 5 cm. Assume a packing factor of 70% and a DC voltage of 12 V. If $NI = 1000$ ampere-turns, find the bare wire diameter, the number of turns N, and the current density.

Test for understanding

List 3 components that will need to be present in the coil space that will reduce the conductor cross sectional area.

Coil Time Constant and Impedance

Why

Often the dynamic operation of an actuator is important

This will depend on the:

- Electric time constant
- And the mechanical time constant (***J/b***)

$$I = \frac{V}{R}(1 - e^{-t/\tau_e}) \quad (12.7)$$

How/ Example

The force required for an actuator will define the product of N and I.

Will the choice of N affect the time constant or the power loss?

$$I = \frac{V}{R}(1 - e^{-t/\tau_e}) \quad (12.7)$$

Test for understanding

Which of the following will be affected by the choice of N

a) Power loss
b) Voltage required
c) Time constant
d) a) and b)
e) b) and c)

Skin Effects and Proximity Effects for AC Currents

Why

In L3b we looked at how AC excitation effects the flux and power loss in steel cores.

In this section we will consider how AC excitation effects current carrying conductors.

How

The skin depth equation is the same.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (12.17)$$

When the skin depth is much greater than the wire radius:

$$\frac{P_e}{v} = \frac{\omega^2 \sigma}{24}\left(w_y^2 B_x^2 + w_x^2 B_y^2\right) (12.18)$$

When the skin depth is less than the wire radius then skin effects losses occur:

$$P = \int \frac{J^2}{\sigma} dv \, (12.19)$$

Litz wire

Litz wire can be used to reduce the skin effects by reducing the diameter of each conductor.

It also reduces "proximity" effects by transposing the wires to cancel eddy current producing fields.

Example

Example 12.2 Skin Effect in an Isolated Conductor A circular copper wire carrying 100 A peak is placed in air, far from any other materials. If its radius is 10 mm, find its current density and magnetic flux density distributions at 400 Hz and 1 Hz using Maxwell. Also find the power loss and resistance per meter.

Test for understanding

Use FEMM to find:

- Power loss
- Flux line plot
- Eddy current distribution

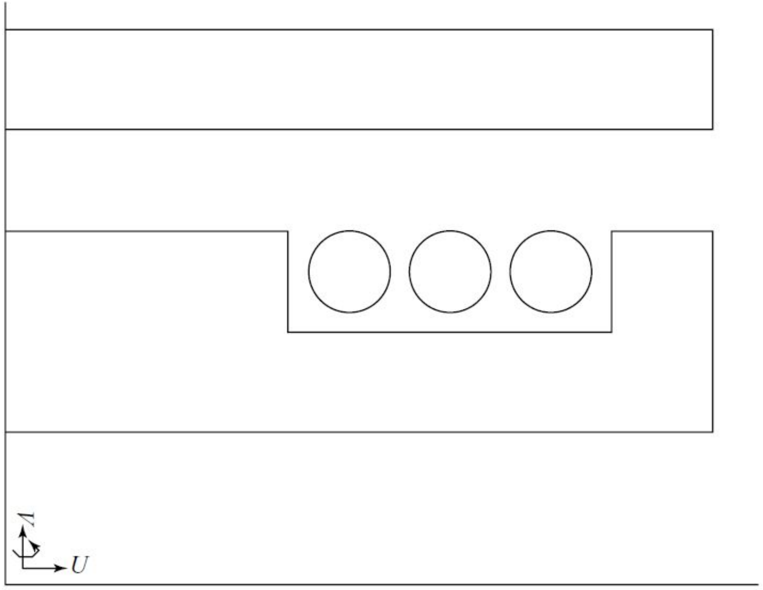

FIGURE E12.3.1 Three-turn winding in ferrite cup core inductor, as drawn in Maxwell's default window. The wire radius is 4 mm.

Example 12.3 Skin and Proximity Effects in Stator Coil with Clapper An axisymmetric copper coil is placed in a ferrite "cup core" inductor shown in Figure E12.3.1 as created in Maxwell's default drawing area. The area is assumed to confine the flux. The ferrite in the lower stator and upper clapper armature has a relative permeability of 1000 and conductivity of 0.01 S/m. The coil has three copper conductors, each of radius 4 mm and carrying 50 A 400 Hz. Use Maxwell to find the power loss, flux line plot, and current density distribution, showing skin and proximity effects in the three wires.

Thermal Conduction

Why - Conduction

Heat is usually the limiting factor that defines how much force can be obtained from a given actuator.

How - Conduction

Governing equation:

$$\nabla \cdot k \nabla T = -\frac{P}{v} \quad (12.20)$$

k - Thermal conductivity (material property)

T - Temperature

P - Power

v - volume

Example 12.4

Compute the temperature distribution

Example 12.4 Steady Thermal Conduction Computation Using Analogy to Electrostatics An axisymmetric copper coil is surrounded by glastic insulation and a cylindrical steel core as shown in Figure E12.4.1. The thermal conductivities are

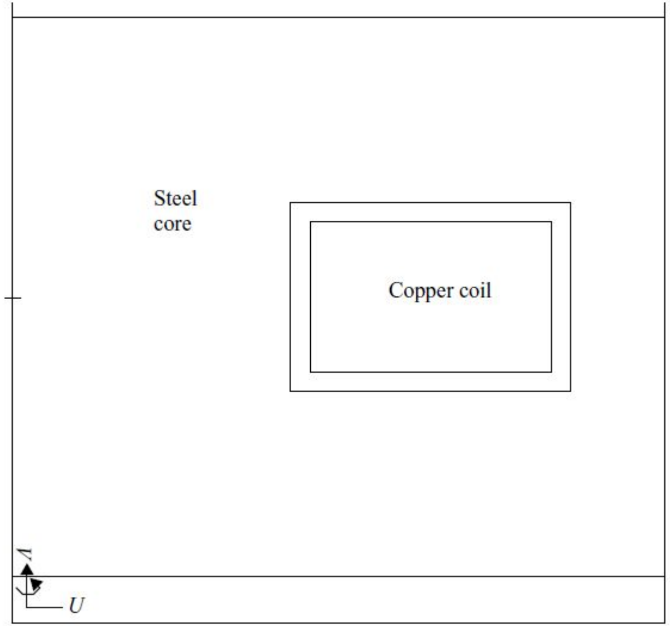

FIGURE E12.4.1 Axisymmetric inductor of radius 70 mm and height 60 mm. The temperature distribution is to be computed when there are power losses in the steel and in the copper coil of size 26 mm radially and 16 mm high, surrounded by glastic insulation 2 mm thick on all sides.

Summary

While in FEA it is fine to have a rectangle with NI, in reality this needs to be a coil that is designed with real wire (What N, what d)?

- Choose N for available voltage
- The choice of N will not affect the time constant or the power loss

Fill factor is affected by:

- Wire diameter (hence possible packing)
- Enamel thickness
- Bobbin or core insulation

FEMM can model conduction heat transfer