Powder Core Loss Calculation

Core loss is generated by the changing magnetic flux field within a material, since no magnetic materials exhibit perfectly efficient magnetic response. Core loss density (PL) is a function of half of the AC flux swing (½ $\triangle B = B_{pk}$) and frequency (f). It can be approximated from core loss charts or the curve fit loss equation:

$$PL = aB_{pk}^{\ b} f^c$$

where a, b, c are constants determined from curve fitting, and B_{pk} is defined as half of the AC flux swing:

$$B_{pk} = \frac{\triangle B}{2} = \frac{B_{AC\,max} - B_{AC\,min}}{2}$$

Units typically used are (mW/cm^3) for PL; Tesla (T) for B_{pk}; and (kHz) for f.
The task of core loss calculation is to determine B_{pk} from known design parameters.

Method 1 – Determine B_{pk} from DC Magnetization Curve. $B_{pk} = f(H)$

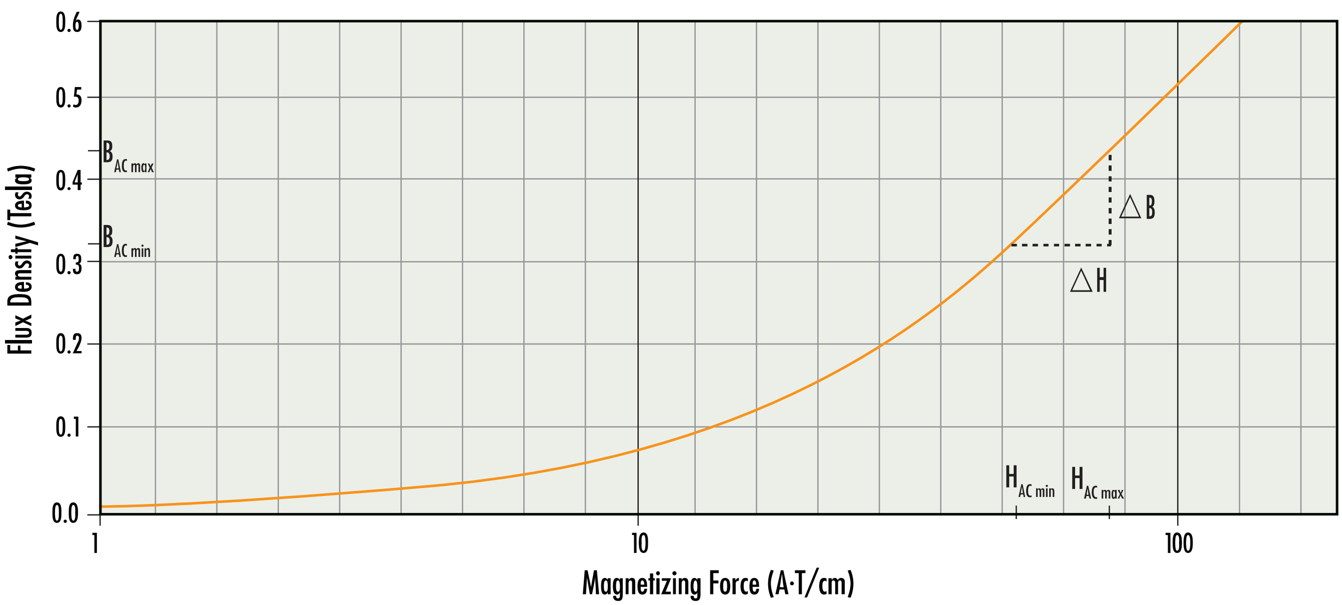
Flux density (B) is a non-linear function of magnetizing field (H), which in turn is a function of winding number of turns (N), current (I), and magnetic path length (l_e). The value of B_{pk} can typically be determined by first calculating H at each AC extreme:

$$H_{ACmax} = \left[\frac{N}{l_e}\left(I_{DC} + \frac{\Delta I}{2}\right)\right]$$

$$H_{ACmin} = \left[\frac{N}{l_e}\left(I_{DC} - \frac{\Delta I}{2}\right)\right]$$

Units typically used are (A·T/cm) for H.
From $H_{AC\,max}$, $H_{AC\,min}$, and the BH curve or equation (listed as DC Magnetization, pgs. 47 - 50) $B_{AC\,max}$, $B_{AC\,min}$ and therefore B_{pk} can be determined.

60µ Kool Mµ DC Magnetization (Example 2)



Example 1 - AC current is 10% of DC current:

Approximate the core loss of an inductor with 20 turns wound on Kool Mµ p/n 77894A7 p. 76 (60µ, l_e=6.35 cm, A_e=0.654 cm^2, A_L=75 nH/T^2). Inductor current is 20 Amps DC with ripple of 2 Amps peak-peak at 100kHz.

1.) Calculate H and determine B from BH curve (p. 48) or curve fit equation (p. 50):

$$H_{ACmax} = \frac{20}{6.35}\left(20 + \frac{2}{2}\right) = 66.14\ ^{A\cdot T}\!/_{cm} \rightarrow B_{ACmax} \cong 0.40T$$

$$H_{ACmin} = \frac{20}{6.35}\left(20 - \frac{2}{2}\right) = 59.84\ ^{A\cdot T}\!/_{cm} \rightarrow B_{ACmin} \cong 0.37T$$

$$\rightarrow B_{pk} = \frac{\triangle B}{2} = \frac{0.40 - 0.37}{2} = 0.015T$$

2.) Determine Core Loss density from chart or calculate from loss equation p. 46:

$$PL = (62.65)(0.015^{1.781})(100^{1.36}) \cong 18.5\ \frac{mW}{cm^3}$$

3.) Calculate core loss:

$$P_{fe} = (PL)(l_e)(A_e) \sim (18.5)(6.35)(0.654) \cong 77mW$$

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Example 2 - AC current is 40% of DC current:

Approximate the core loss for the same 20-turn inductor, with same inductor current of 20 Amps DC but ripple of 8 Amps peak-peak at 100kHz.

1.) Calculate *H* and determine *B* from BH curve fit equation p. 50:

$$H_{ACmax} = \frac{20}{6.35}\left(20+\frac{8}{2}\right) = 75.59\ {}^{A\cdot T}/_{cm} \rightarrow B_{ACmax} \cong 0.44T$$

$$H_{ACmin} = \frac{20}{6.35}\left(20-\frac{8}{2}\right) = 50.39\ {}^{A\cdot T}/_{cm} \rightarrow B_{ACmin} \cong 0.33T$$

$$\rightarrow B_{pk} = \frac{\triangle B}{2} = \frac{0.44-0.33}{2} = 0.055T$$

2.) Determine Core Loss density from chart or calculate from loss equation p. 46: $PL = (62.65)(0.055^{1.781})(100^{1.36}) \cong 188\ \frac{mW}{cm^3}$

3.) Calculate core loss: $P_{fe} = (PL)(l_e)(A_e) = (188)(6.35)(0.654) \cong 781mW$

Note: Core losses result only from AC excitation. DC bias applied to any core does not cause any core losses, regardless of the magnitude of the bias.

Example 3 – pure AC, no DC:

Approximate the core loss for the same 20-turn inductor, now with 0 Amps DC and 8 Amps peak-peak at 100kHz.

1.) Calculate H and determine B from BH curve fit equation p. 50:

$$H_{ACmax} = \frac{20}{6.35}\left(+\frac{8}{2}\right) = 12.60\ {}^{A\cdot T}/_{cm} \rightarrow B_{ACmax} \cong 0.092T$$

$$H_{ACmin} = \frac{20}{6.35}\left(-\frac{8}{2}\right) = -12.60\ {}^{A\cdot T}/_{cm} \rightarrow B_{ACmin} \cong -0.092T$$

$$\rightarrow B_{pk} = \frac{\triangle B}{2} \sim 0.092T$$

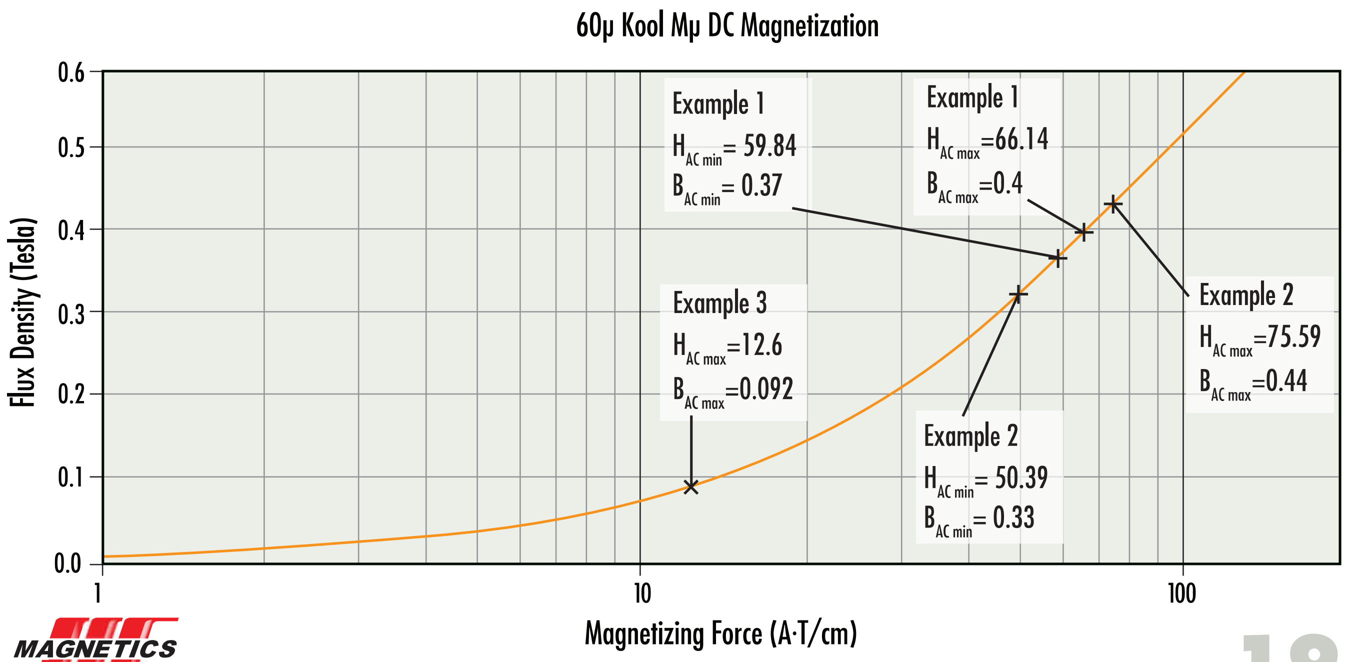
Note: Curve fit equations are not valid for negative values of B. Evaluate for the absolute value of B, then reverse the sign of the resulting H value.

2.) Determine Core Loss density from chart or calculate from loss equation p. 46.

$$PL = (62.65)(0.092^{1.781})(100^{1.36}) \cong 470\ \frac{mW}{cm^3}$$

3.) Calculate core loss: $P_{fe} = (PL)(l_e)(A_e) = (470)(6.35)(0.654) \cong 1.95W$

Plotted below are the operating ranges for each of the three examples.
Note the significant influence of DC bias on core loss, comparing Example 3 with Example 2. Lower permeability results in less B_{pk}, even if the current ripple is the same. This effect can be achieved with DC bias, or by selecting a lower permeability material.



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Method 2, for small △H, approximate B_{pk} from effective perm with DC bias.
$B_{pk} = f(\mu_e, \triangle H)$

The instantaneous slope of the BH curve is defined as the absolute permeability, which is the product of permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$) and the material permeability (μ), which varies along the BH curve. For small AC, this slope can be modeled as a constant throughout AC excitation, with μ approximated as the effective perm at DC bias (μ_e):

$$\frac{dB}{dH} = \mu_0\mu_e \quad \rightarrow \frac{\triangle B}{\triangle H} = \mu_0\mu_e \quad \rightarrow \triangle B = \mu_0\mu_e \triangle H \quad B_{pk} = \frac{\triangle B}{2} = (0.5)\,\mu_0\mu_e \triangle H$$

The effective perm with DC bias is shown in this catalog as % of initial perm and can be obtained from the DC bias curve or curve fit equation, pgs 29 - 34

$$B_{pk} = (0.5)(\mu_0)(\%\mu_i)(\mu_i)(100)(\triangle H) \quad \text{where} \quad \triangle H = \frac{N\triangle I}{l_e}$$

△H is multiplied by 100 because l_e is expressed in cm, while B_{pk} units include m.

Reworking Example 1 (20 Amps DC, 2 Amps pk-pk)

$$H_{DC} = \left[\frac{20}{6.35}(20)\right] = 63\ ^{A\cdot T}\!/_{cm} \quad \rightarrow \quad \text{from curve or curve fit equation, } \%\mu_i = 0.58$$

$$\mu_i = 60$$

$$\triangle H = \frac{N\triangle I}{l_e} = \frac{20(2)}{6.35} = 6.3\ ^{A\cdot T}\!/_{cm}$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(0.58)(60)(100)(6.3) \cong 0.014\text{T} \quad \text{(this compares to 0.015T using Method 1)}$$

Reworking Example 2 (20 Amps DC, 8 Amps pk-pk)

From example 1,

$$H_{DC} = 63\ ^{A\cdot T}\!/_{cm}, \%\mu_i = 0.58;\ \mu_i = 60$$

$$\triangle H = \frac{N\triangle I}{l_e} = \frac{20(8)}{6.35} = 25.2\ ^{A\cdot T}\!/_{cm}$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(0.58)(60)(100)(25.2) = 0.055\text{T} \quad \text{(this compares to 0.055T using Method 1)}$$

Reworking Example 3 (0 Amps DC, 8 Amps pk-pk)

From example 2,

$$\triangle H = 25.20\ ^{A\cdot T}\!/_{cm}$$

$$H_{DC} = 0\ ^{A\cdot T}\!/_{cm} \quad \%\mu_i = 1$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(1)(60)(100)(25.2) = 0.095\text{T} \quad \text{(this compares to 0.092T using Method 1)}$$

Powder Core Loss Calculation

Method 3, for small $\triangle H$, determine B_{pk} from biased inductance. $B_{pk} = f(L, I)$

B can be rewritten in terms of inductance by considering Faraday's equation and its effect on inductor current:

$$V_L = NA\frac{dB}{dt} = L\frac{dI}{dt} \rightarrow dB = \frac{L}{NA}dI$$

L varies non-linearly with I. For small AC, L can be assumed constant throughout AC excitation and is approximated by the biased inductance (L_{DC}).

$$\triangle B = \frac{L_{DC}\triangle I}{NA} \rightarrow B_{pk} = \frac{L_{DC}\triangle I}{2NA_e}$$

Another way of looking at this is by rewriting the relationship between B and L as:

$$\rightarrow \frac{dB}{dH} = \frac{L}{NA}\frac{dI}{dH}$$

Substituting (dH/dI) with (N/l_e) and A with A_e:

$$\rightarrow \frac{dB}{dH} = \frac{L\,l_e}{N^2A_e}$$

L varies non-linearly with H. For small AC, the slope of the BH curve is assumed constant throughout AC excitation, and L is approximated by the biased inductance (L_{DC}).

$$\frac{\triangle B}{\triangle H} = \frac{L_{DC}l_e}{N^2A_e} \rightarrow \triangle B = \frac{L_{DC}\,l_e}{N^2A_e}\triangle H = \frac{L_{DC}\triangle I}{NA_e} \rightarrow \triangle B_{pk} = \frac{L_{DC}\triangle I}{2NA_e}$$

Powder Core Loss Calculation

Reworking Example 1:

$$L_{nl}\,(\text{no load}) = (A_L)(N^2) = (75\,nH/T^2)(20^2) = 30\mu H$$

$$L_{DC}\,(20A) = (\%\mu_i)(L_{nl}) = (0.58)(30) = 17.4\mu H$$

$$\rightarrow B_{pk} = \frac{(17.4)(10^{-6})(2)}{2(20)(0.654)(10^{-4})} = 0.013T$$ (this compares to 0.015T per Method 1, 0.014T per Method 2).

Reworking Example 2:

From example 1, $L_{DC} = 17.4\mu H$

$$\rightarrow B_{pk} = \frac{(17.4)(10^{-6})(8)}{2(20)(0.654)(10^{-4})} = 0.053T$$ (this compares to 0.055T per Method 1, 0.055T per Method 2).

Reworking Example 3:

$$L_{DC} = L_{nl} = 30\mu H$$

$$\rightarrow B_{pk} = \frac{(30)(10^{-6})(8)}{2(20)(0.654)(10^{-4})} = 0.092T$$ (this compares to 0.092T per Method 1, 0.095T per Method 2).

The plot below illustrates the difference between Method 1 and Method 2