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The Thermal COMSOL FEM Model

of Frenetic

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Version History

Version	Date	Changes from	Comments
1.0	February 2026	Richard Schlesinger	First release

01 Model Features and Accuracy

Model features

- Calculates hotspot temperature & location for natural convection
- 2D FEM model using COMSOL Multiphysics
- Physical model based on
  - HF conduction losses
  - Heat conduction within solids (and stagnant air)
  - Convection boundary conditions based on common empirical formulae
  - Radiation to the exterior

Model accuracy

- 4.8-12.1% error measured on 4 different magnetics, average 8.5%

02 Why a Thermal Model?

Materials in magnetics constrain the maximum temperature before thermal breakdown. Furthermore, significant temperature gradients within the component can lead to mechanical stresses, and, incorporating a thermal model enhances the accuracy of loss calculations, as material losses are inherently temperature-dependent. A thermal model is required to predict the hotspot temperature and temperature distribution within the magnetic component to prevent operating the magnetic within an acceptable temperature range.

03 How does it work?

Model concept

1. the 3D magnetic component is modelled using the 2D Inside-Window (IW) cross-section shown in Figure 1
2. heat sources: high-frequency conduction loss distribution is calculated
3. temperature distribution is calculated based on **heat sources**:
   a. high frequency conduction loss distribution
   b. homogeneous core loss distribution based on the well-known iGSE-model [1]

   and **heat dissipation** to the exterior:
   c. convection based on common empirical formulae [2]
   d. radiation from surfaces facing the exterior
4. losses & magnetic field recalculated with temperature-dependent copper conductivity
5. Temperature distribution is recalculated based on updated loss distribution
6. Steps 4&5 are repeated until convergence

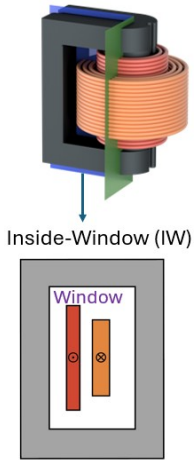


Figure 1 - Inside-Window (IW) cross section

Equations

The partial differential equation system consists of a coupled electromagnetic & thermal subsystem. The electromagnetic equations are governed by

Electromagnetic system: Maxwell's equations

$$\vec{\nabla} \times \vec{H} = \sigma \vec{E} + \vec{J}_{ext}$$

$$\vec{E} = -j\omega \vec{A}$$

Where $\vec{J}_{ext}$ is the external current density coming from the winding currents (model input), and $\vec{A}$ is the magnetic vector potential that the system is being solved for.

Thermal system: Energy balance

$$\vec{\nabla} \cdot \vec{q} = d_z Q$$

Where $\vec{q}$ is the in-plane heat flow, d_z is the out-of-plane thickness, and Q is the heat source density coming from core- and winding losses. Winding losses are computed as $p = \frac{1}{\sigma} J^2$. The system is insulated in out-of-plane direction

Obtaining the hotspot temperature

The temperature distribution is calculated in the IW-cross section from Figure 1 with the air assumed as thermally conductive medium. The system is cooled via the core boundaries via convection and radiation. The thermal hotspot is taken from this calculation.

Model Assumptions & Limitations

Thermal modelling is subject to complex physical processes. In particular, thermal heat distribution is inherently a 3-dimensional problem that is governed by fluid dynamics due to convective heat transfer.

To achieve reasonable calculation speed, an automated thermal model demands more constricting assumptions than other physical domains. In particular,

- The model needs to be 2D instead of 3D
- Fluid dynamic processes are modelled by common empirical formulae [2] rather than by a coupled computational fluid dynamic simulation

The resulting 2D model comes with the following assumptions:

- Simplification: ratio of heat generation/heat dissipation is assumed to be constant in all cross sections of the magnetic component
  - No heat flow in out-of-plane direction
- Homogeneous core loss distribution
- Constant ambient temperature

04 Verification

Benchmark Transformers

The model was verified with 4 different transformer prototypes with a wide geometrical variation to ensure the reliability of the model concept.

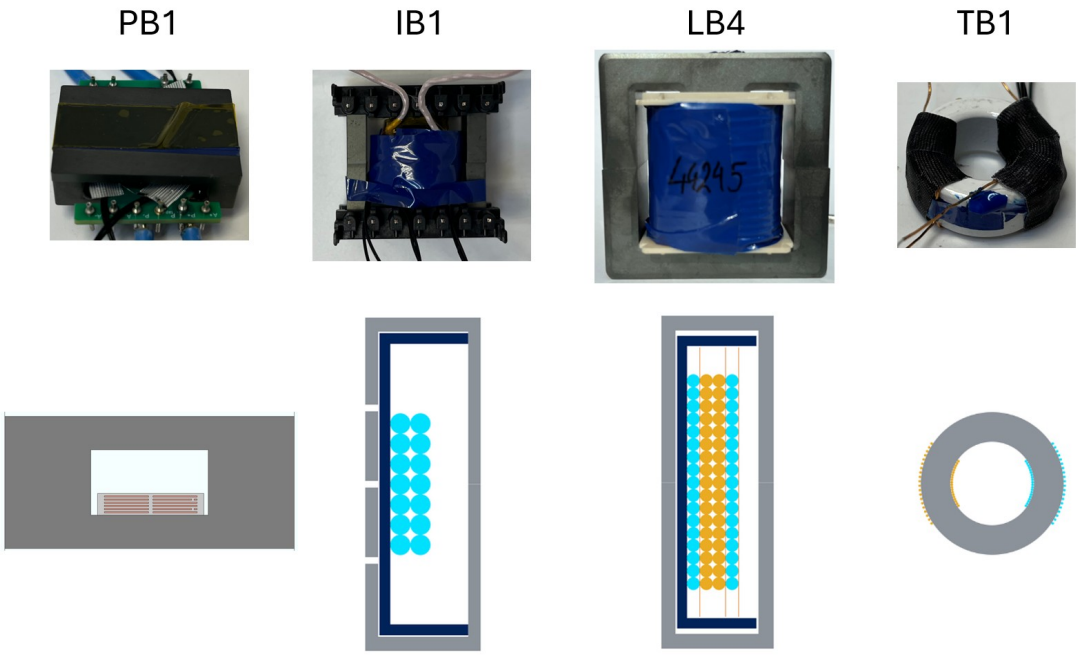


Figure 2 - Transformer prototypes

Table 1 - Transformer Prototype data

Magnetic	Core	Type	Wires	Filling Factor	N1/N2/N3
PB1	EQ38/8/25, 3C95	Planar	3.6mmx0.106mm	30.1%	8/4/2
IB1	E32/16/11, 3C96	Inductor	Litz 25xØ0.2mm	26.3%	14
LB4	E55/28/21, 3C92	Transformer	Litz 240xØ0.07mm	54.6%	17/34
TB1	TX25/15/10, 3C94	Toroid	Round Ø0.4mm	4.5%	20/20

Verification Results

The purpose of the measurement is to verify the 2D thermal model approach, i.e. checking heat distribution, generation, and dissipation for plausibility. Therefore, DC measurements and an AC-short circuit measurement (all without core losses) were performed to avoid introducing uncertainty by a core loss model/measurement and purely verify the thermal model. Table 2 summarizes the results. The table shows that the error ranges between 4.8% and 12.1% on the measured prototypes, averaging at 8.5%. The good agreement proves that the underlying assumptions are justified for the tested cases with natural convection.

Table 2 - Model & measurement results

		Measurement			Model		
Magnetic	**Mode**	**T amb [°C]**	**T max [°C]**	**ΔT (K)**	**T max [°C]**	**ΔT (K)**	**Error**
PB1	AC, 150 kHz, 6.9A	25.7	63.8	38.1	66.2	40.5	6.2%
IB1	DC, 10A	19.9	86.6	66.7	94.7	74.8	12.1%
LB4	DC, 7.55A	20.8	92.0	71.2	88.6	67.8	−4.8%
TB1	DC, 3A	20.7	68.5	47.8	73.8	53.1	11.0%
Average							**8.5%**

Figure 3 through Figure 6 show the temperature distribution and location of the hotspot in the four magnetic components. The temperature distributions reflect how the heat is generated in the wires through conduction losses and distributed to the outside via the window air and dissipated at the core boundaries via convection and radiation.

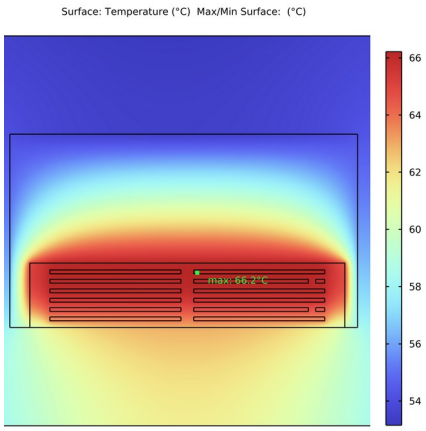


Figure 3 - Temperature distribution PB1

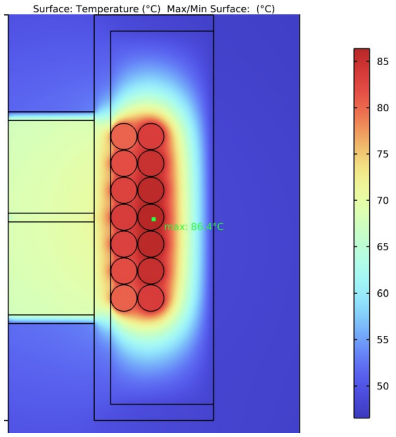


Figure 4 - Temperature distribution IB1

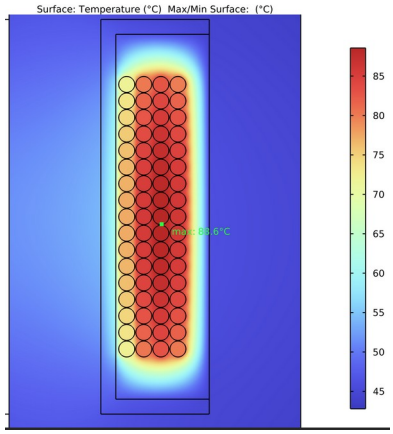


Figure 5 - Temperature distribution LB4

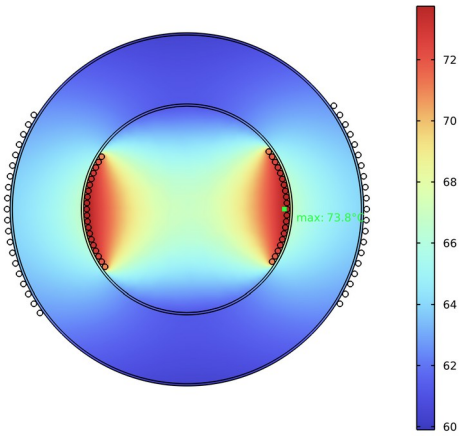


Figure 6 - Temperature distribution TB1

05 Measurement Setup

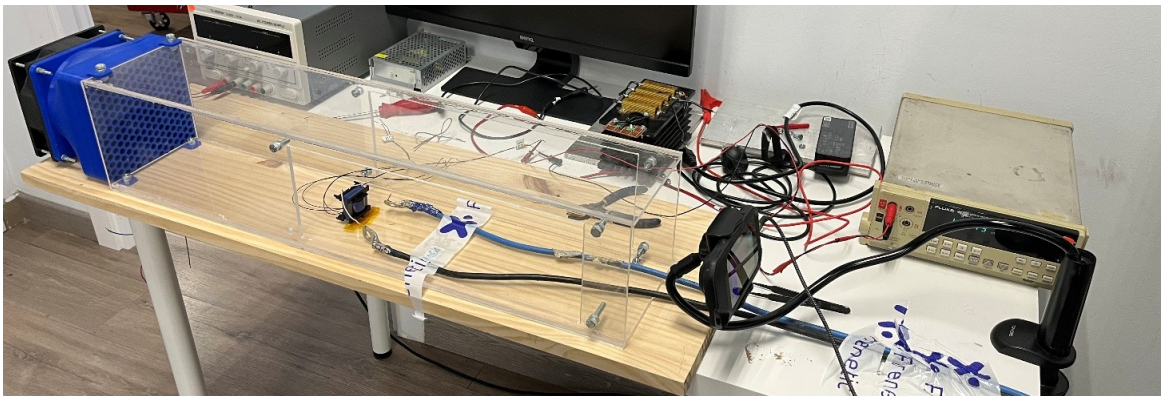


Figure 7 - Measurement Setup

Figure 7 shows the measurement setup with the IB1 inductor connected. The temperature was measured with a NTC thermistor 10kOhm 3988K by EPCOS TDK Electronics. It is important to note that the position of the thermistors is crucial in tapping the right temperature. Hence, the thermistors were placed in the center of the windings inside the tightly-wound wires in the wire-wound transformers, and on top of the PCB in the planar transformer, respectively. The validity of the temperature measurements was double-checked with a FLIR C3 thermal camera. The ambient temperature was measured with a K-Type thermocouple at each measurement to get the correct temperature lift.

06 Conclusion & Outlook

The measurements presented in this model factsheet show that the simplifications chosen in the thermal model approach reach a good level of accuracy with an average model error of 8.5% for the inspected prototypes. Some of the assumptions rather under-/overestimate the generated heat, while some assumptions under-/overestimate the dissipated heat. These simplifications balance out well leading to accurate hotspot temperatures over a wide range of magnetic prototype geometries.

Future model adaptions contain inclusion of forced convection. Preliminary results show that the model approach has to be slightly modified to account for the convection flow in out-of-plane direction in the presence of a forced air flow.

07 References

[1] J. Mühlethaler, J. Biela, J. W. Kolar, and A. Ecklebe, “Improved core-loss calculation for magnetic components employed in power electronic systems,” *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 964–973, 2012, doi: 10.1109/TPEL.2011.2162252.

[2] P. Stephan, S. Kabelac, M. Kind, H. Martin, D. Mewes, and K. Schaber, *VDI Heat Atlas*, 2nd edition. Springer Berlin Heidelberg, 2010. doi: 10.1007/978-3-540-77877-6.



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