Theme 6
High-Energy-Density Wound Passive Components

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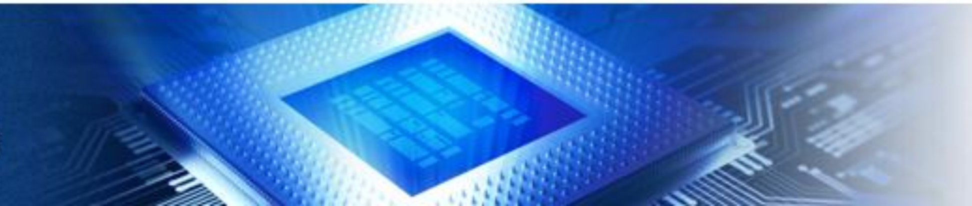


Introduction

- The aim of this research theme is to develop **high-energy-density**, low-weight and volume wound passive components for automotive power converters.
- To achieve the **high-energy-density** design objective both the appropriate design methodology, material and inductor topology are considered.
- The measure of improvement for the new **high-energy-density** inductor designs is based on an energy density factor benchmarking against the existing, commercially available inductor designs.

Design methodology

- The methodology developed for design of the **high-energy-density** wound passive components utilises the multi-physics approach, where both the electromagnetic and thermal effects are consider simultaneously.
- To provide an accurate and computationally efficient design-optimisation methodology an advancement in mathematical design-analysis tools was required including:

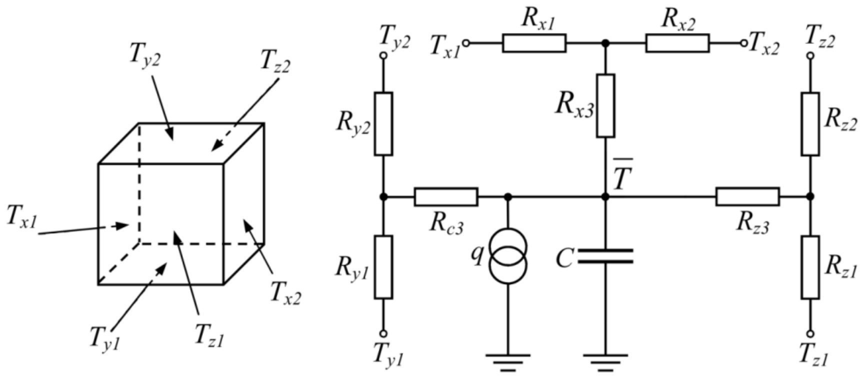
- **thermal analysis**
- **material thermal data**
- **power loss analysis**

Thermal analysis

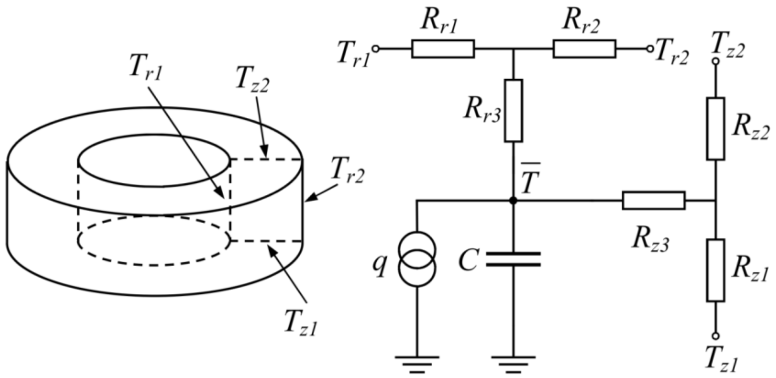
- The lumped parameter equivalent thermal circuit approach utilising **cuboidal** and **arc** elements was developed to provide the required accuracy and low-solving time.
- The developed method accounts for anisotropic material properties, internal heat generation and allows for a more intuitive model construction.

Thermal analysis

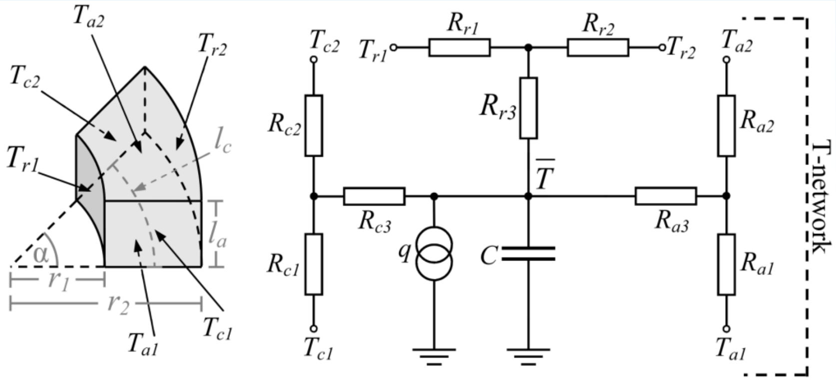
Cuboidal element



Cylindrical element



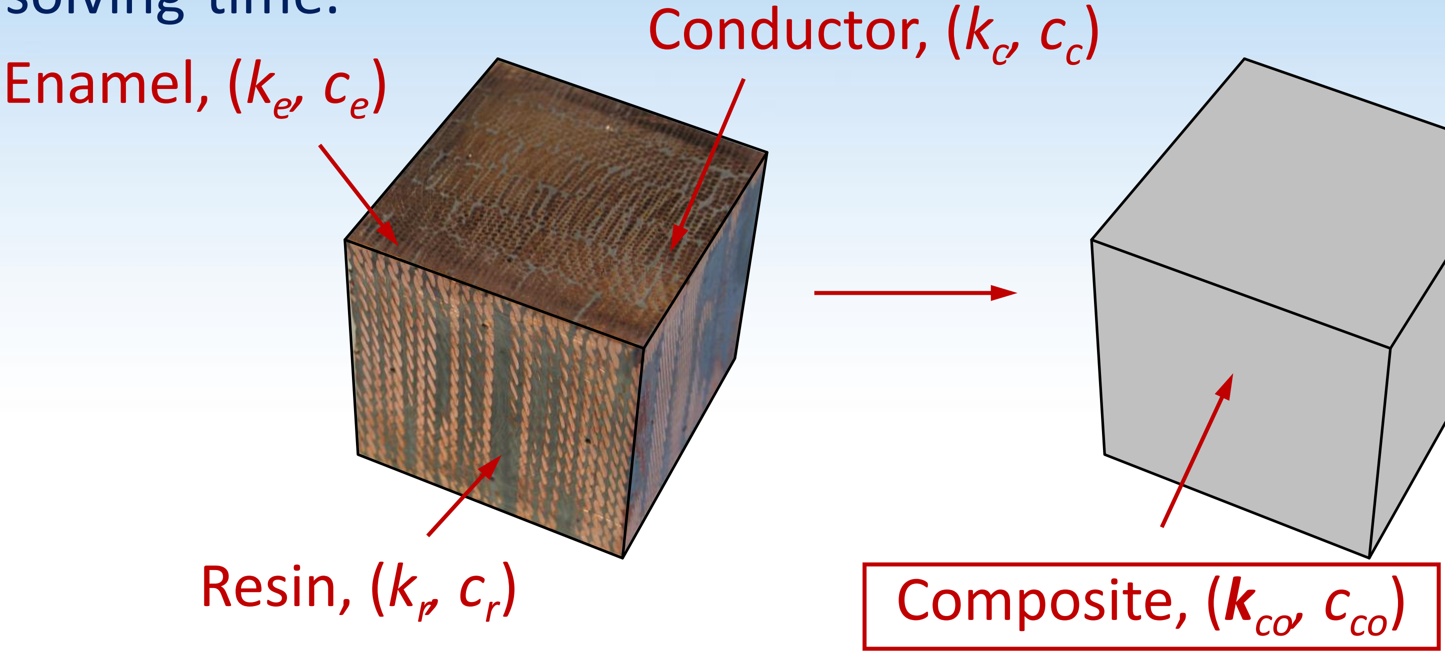
Arc-segment element



Library of the thermal network elements

Material thermal data

- The developed experimental and theoretical methods for deriving the composite material thermal data allow for simplified and more accurate thermal analysis with reduced solving-time.



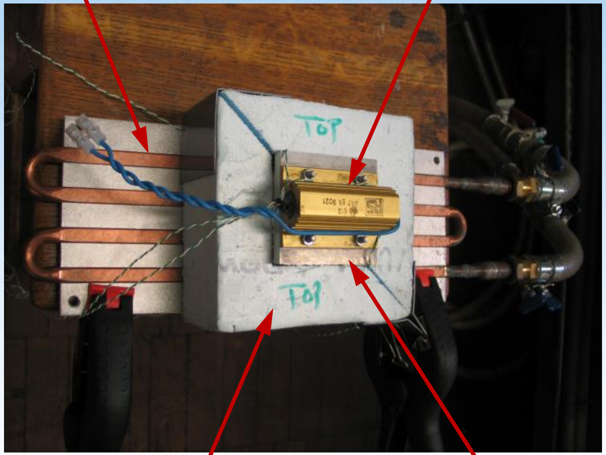
Conductor, (k_c, c_c)

Enamel, (k_e, c_e)

Resin, (k_r, c_r)

Composite, ($\boldsymbol{k_{co}}$, c_{co})

Material thermal data



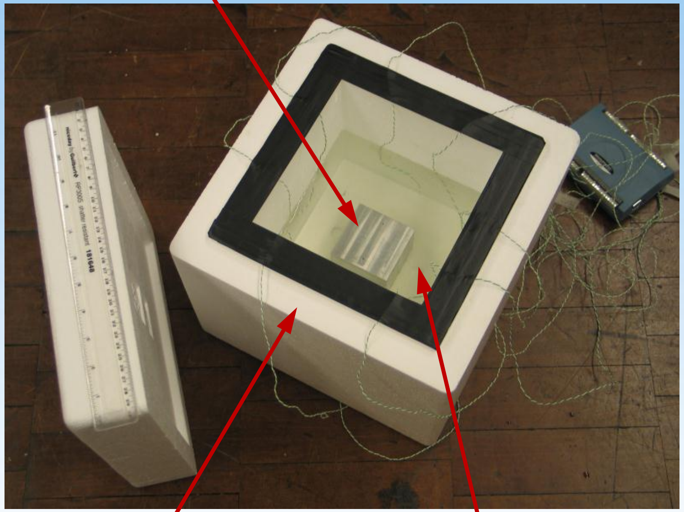
Power resistor

Cold plate

Cube sample

Thermal insulation

$$k_x = \frac{q_x l_x}{A_x \Delta T}$$



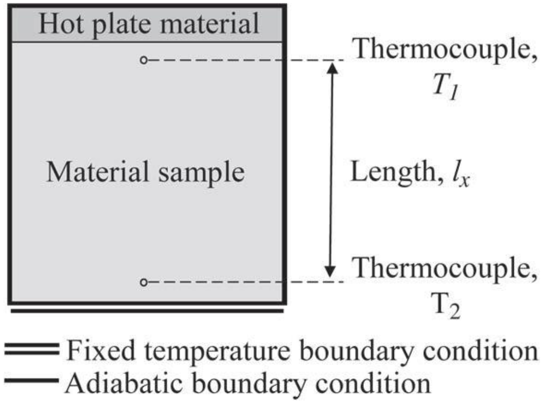
Cube sample

Water

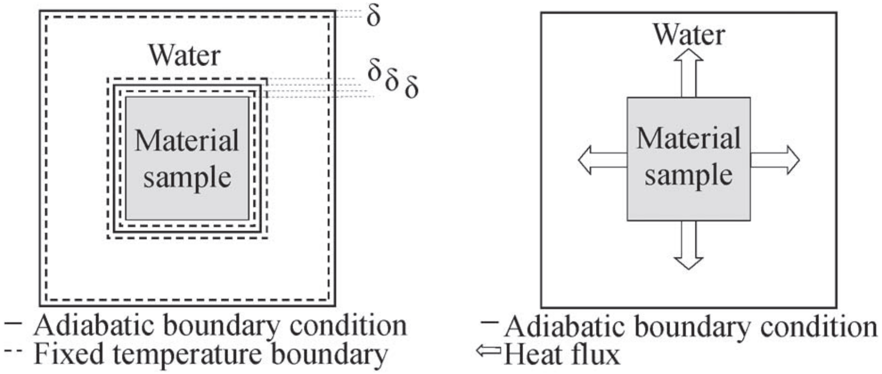
Calorimeter

$$c_p = \frac{m_w c_{pw} \Delta T_w + m_{cal} c_{pcal} \Delta T_{cal}}{m \Delta T}$$

Material thermal data



Thermal conductivity



$t = 0$ $t > 0$

Specific heat capacity

Model equivalents for derivation of the thermal data

Power loss analysis

- The power losses generated within an inductor assembly depend on various effects including the excitation and operating condition. Good understanding of these is crucial in the design-optimisation process.

$$\boxed{P_{ac} = P_{dc} + P_{\ ac\,effects}}$$

$$\left.\frac{P_{ac}}{P_{dc}}\right|_{T=const} = \left.\frac{R_{ac}}{R_{dc}}\right|_{T=const}$$

Power loss analysis

$$P_{ac}|_T = I^2 R_{dc}|_{T_0}\left(1 + \alpha(T - T_0)\right) + I^2\, R_{dc}\Big|_{T_0} \frac{\left(\frac{R_{ac}}{R_{dc}}\right)_{T_0} - 1}{\left(1 + \alpha(T - T_0)\right)^{\beta}}$$

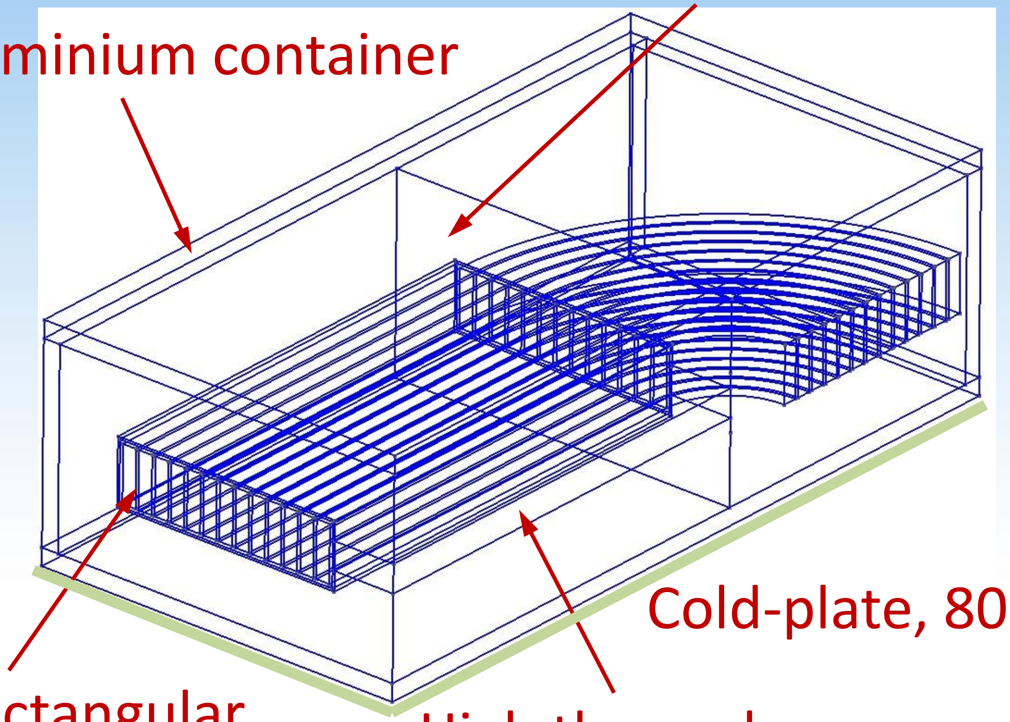
$$\rho\Big|_T = \rho\Big|_{T_0} \left(1 + \alpha(T - T_0)\right)$$

Temperature dependence of winding loss at ac operation

Demonstrator inductor design

- E-core type inductor topology
- $L = 80\mu\text{H}$
- $f = 800\text{Hz}$
- $I = 200\text{A}_{\text{rms}}$
- $E_d \geq 1\ \text{J/kg}$

$$\boxed{E_d = \frac{I^2 L}{m}}$$



Laminated core pack (NO20 silicon-iron)

Aluminium container

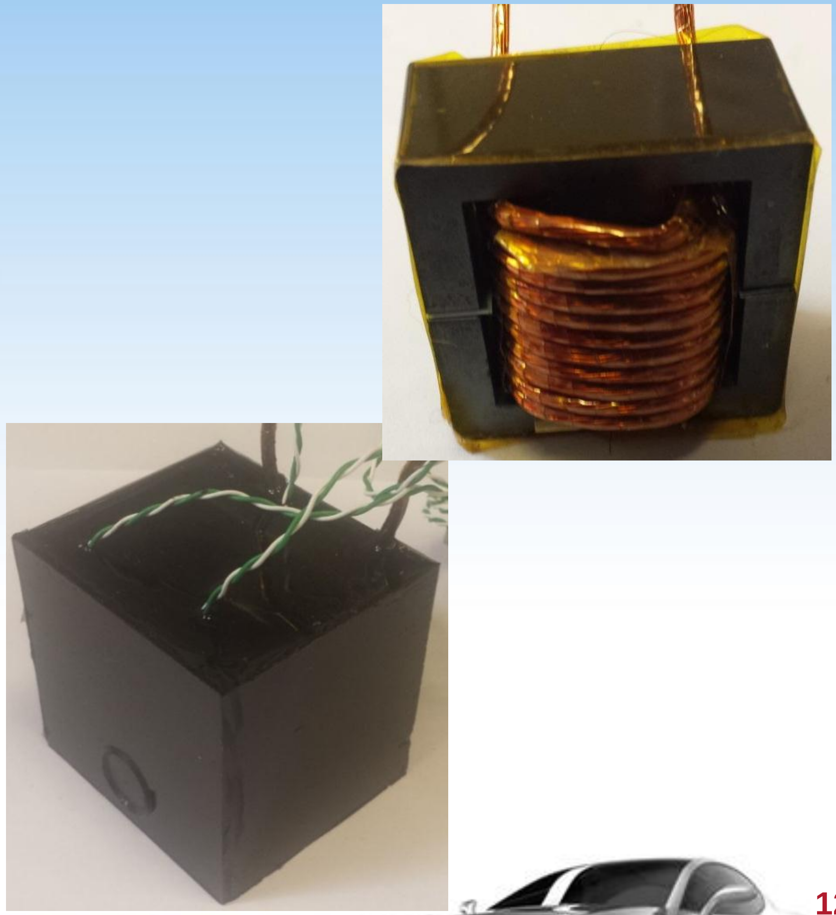
Cold-plate, 80°C

Profiled rectangular aluminium conductors

High thermal conductivity epoxy-resin, $k \approx 1\text{W/m K}$

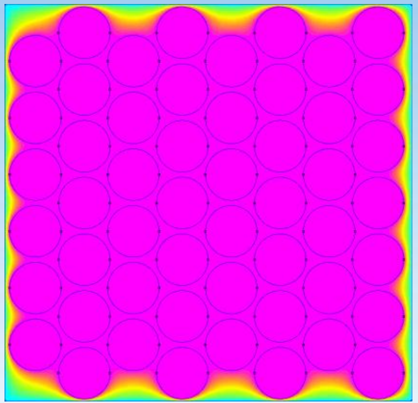
Why use a potting compound?

- To seal the component from the external environment
- To improve the mechanical integrity of the component
- To improve cooling of the component by displacing trapped air within the assembly

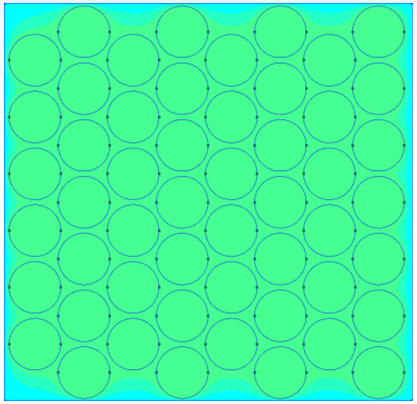


Why use a potting compound - Thermal

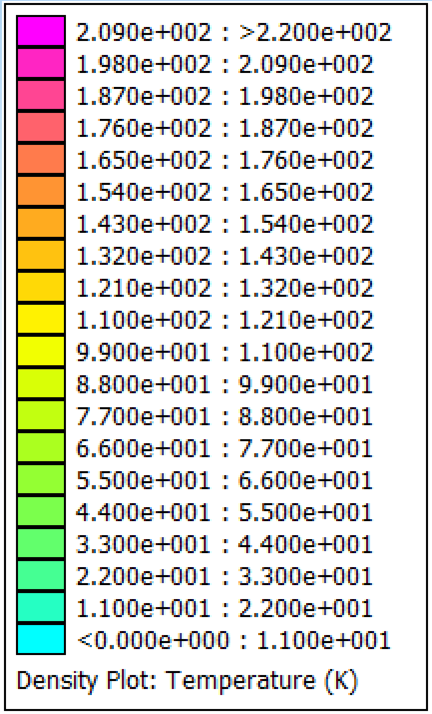
- In wound components windings do not tessellate
- Results in trapped air between wires
- Trapped air has poor thermal conductivity (0.026 W/m.K)
- Potting compound can displace the trapped air and has a higher thermal conductivity



Air



Potting compound



2.090e+002 : >2.200e+002
1.980e+002 : 2.090e+002
1.870e+002 : 1.980e+002
1.760e+002 : 1.870e+002
1.650e+002 : 1.760e+002
1.540e+002 : 1.650e+002
1.430e+002 : 1.540e+002
1.320e+002 : 1.430e+002
1.210e+002 : 1.320e+002
1.100e+002 : 1.210e+002
9.900e+001 : 1.100e+002
8.800e+001 : 9.900e+001
7.700e+001 : 8.800e+001
6.600e+001 : 7.700e+001
5.500e+001 : 6.600e+001
4.400e+001 : 5.500e+001
3.300e+001 : 4.400e+001
2.200e+001 : 3.300e+001
1.100e+001 : 2.200e+001
<0.000e+000 : 1.100e+001

Density Plot: Temperature (K)

Composite potting compounds

- The thermal performance of potting compounds can enhanced through the use of thermally conductive filler materials.
- In our work we consider the effect of adding aluminium oxide powder to epoxy encapsulant
  - Epoxy thermal conductivity (~0.2 W/m.K)
  - Aluminium oxide thermal conductivity (~30 W/m.K)

Filler packing factors

- Filler particles do not fit together without leaving gaps
- Addition of fillers influences other properties of the encapsulant:
  - Viscosity of encapsulant is increased by the inclusion of filler materials
  - Makes the material more difficult to work with
- Maximum filler concentration is limited by the bulk density of the filler
- Methods of quantifying this:
  - Poured density
  - Tapped density

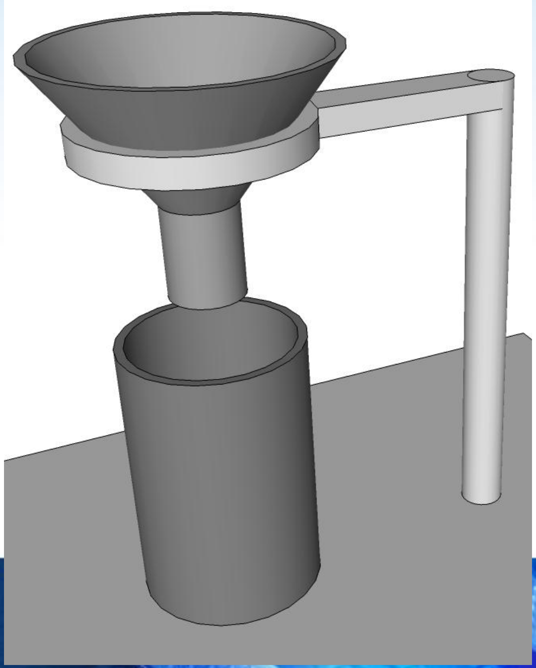
Bulk density of powders

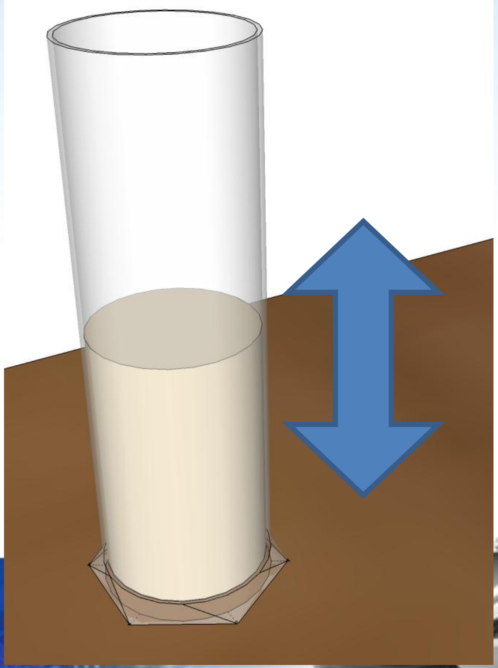
Poured Density

- Powder is poured through a funnel into a vessel of known volume
- Mass of powder filling vessel is measured
  - It is important not to disturb the vessel during pouring

Tapped Density

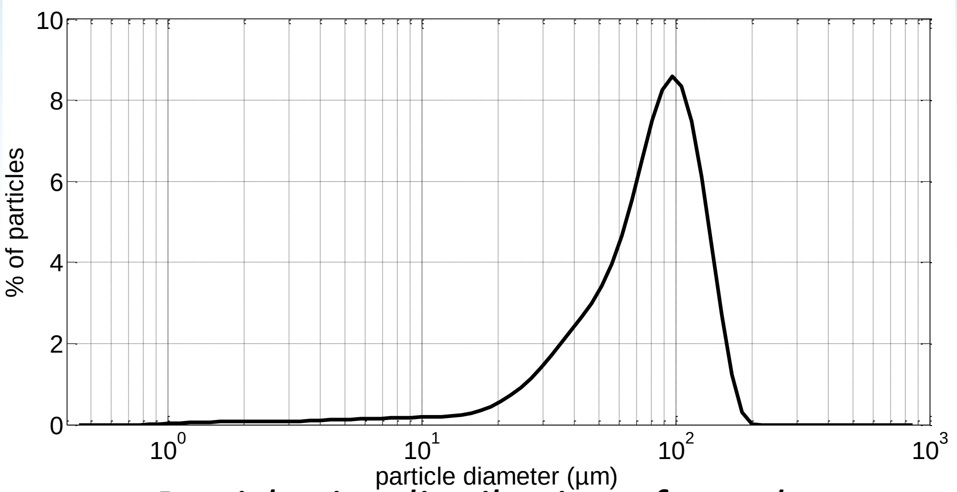
- Sample of known mass is placed in a measuring cylinder
- Cylinder is tapped on a solid surface until volume stabilises
- Volume is measured using cylinder scale



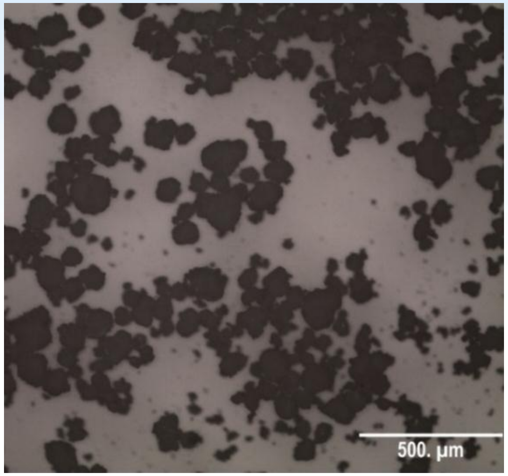


Filler Properties

- The filler used in our work is aluminium oxide powder
  - Theoretical density = 3.97 g/cm^3
  - Thermal conductivity 30 W/m.K
- Poured Density = 0.84 g/cm^3 (21.2% of theoretical density)
- Tapped Density = 1.11 g/cm^3 (28.0% of theoretical density)
- Particles are approximately spherical

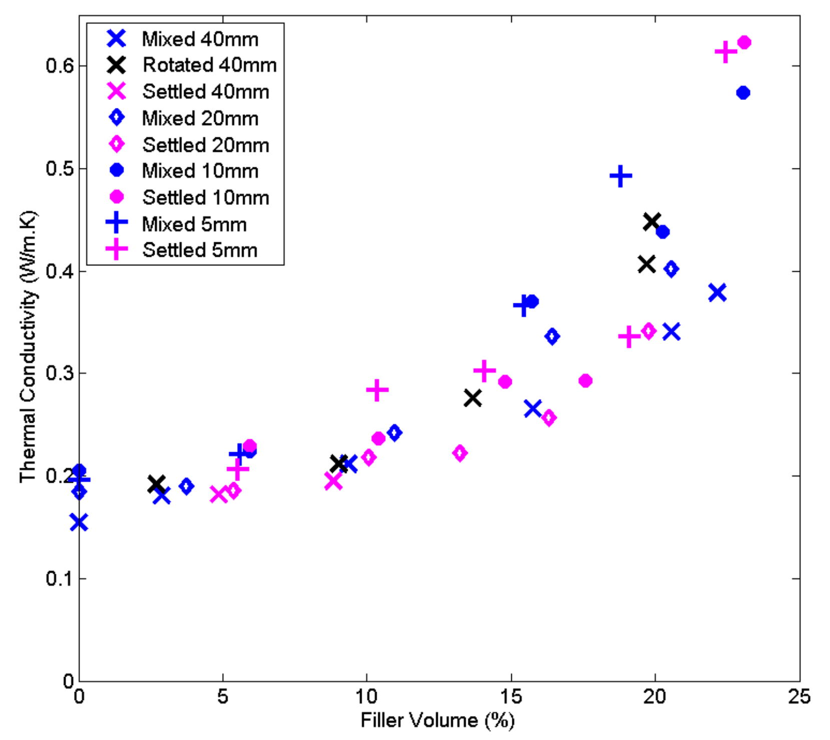


Particle size distribution of powder



Microscope image of powder

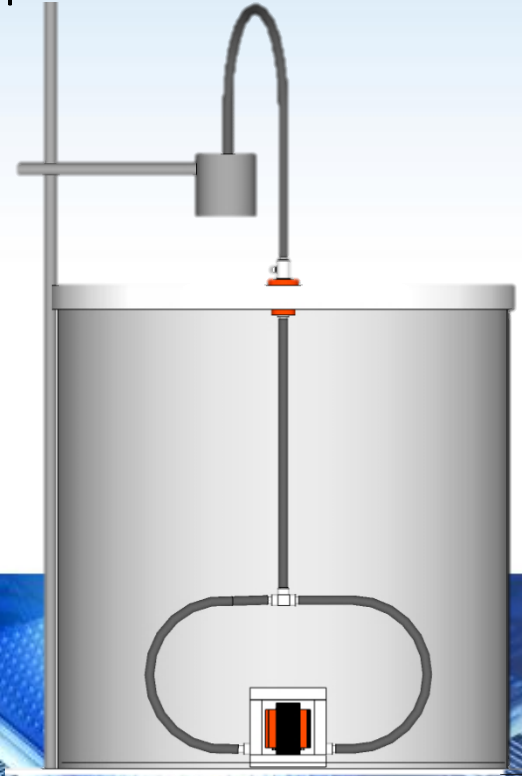
Composite thermal conductivity



- Composite samples were manufactured and tested
- Thermal conductivity of potting compound is increased with filler concentration
- Viscosity of potting compound is also increased
  - The acceptability of this is application specific

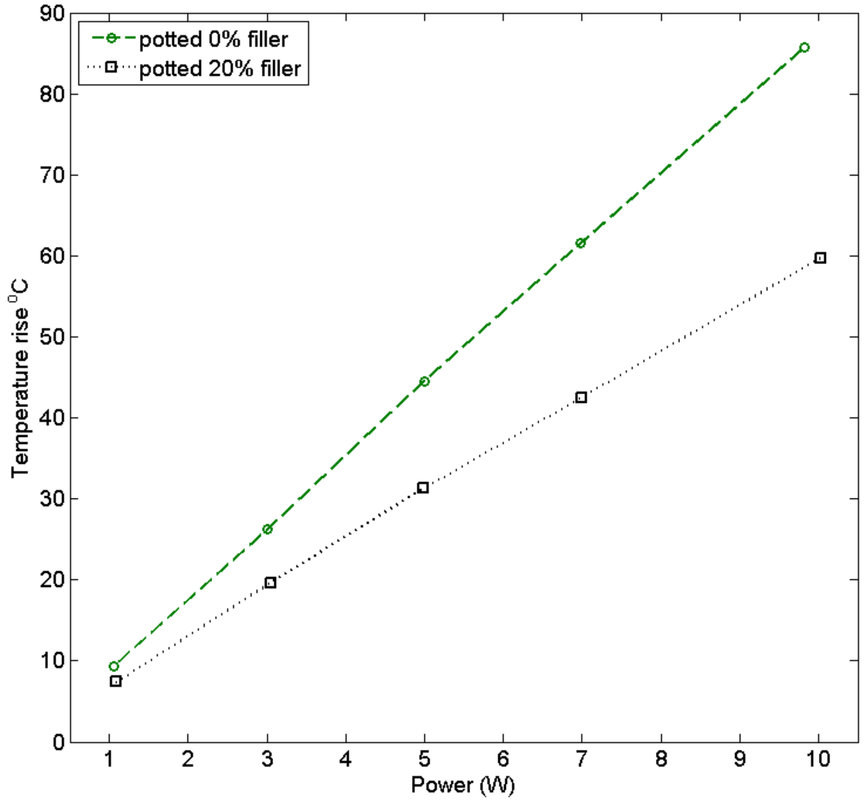
Vacuum potting

- To prevent the entrapment of air within the potting compound process is performed under vacuum
  - Component is placed within the mould which is placed in the chamber
  - Chamber is evacuated
  - Top valve is opened to allow potting compound to be pulled from the header vessel to the mould
  - Top valve is closed
  - Chamber is re-pressurised



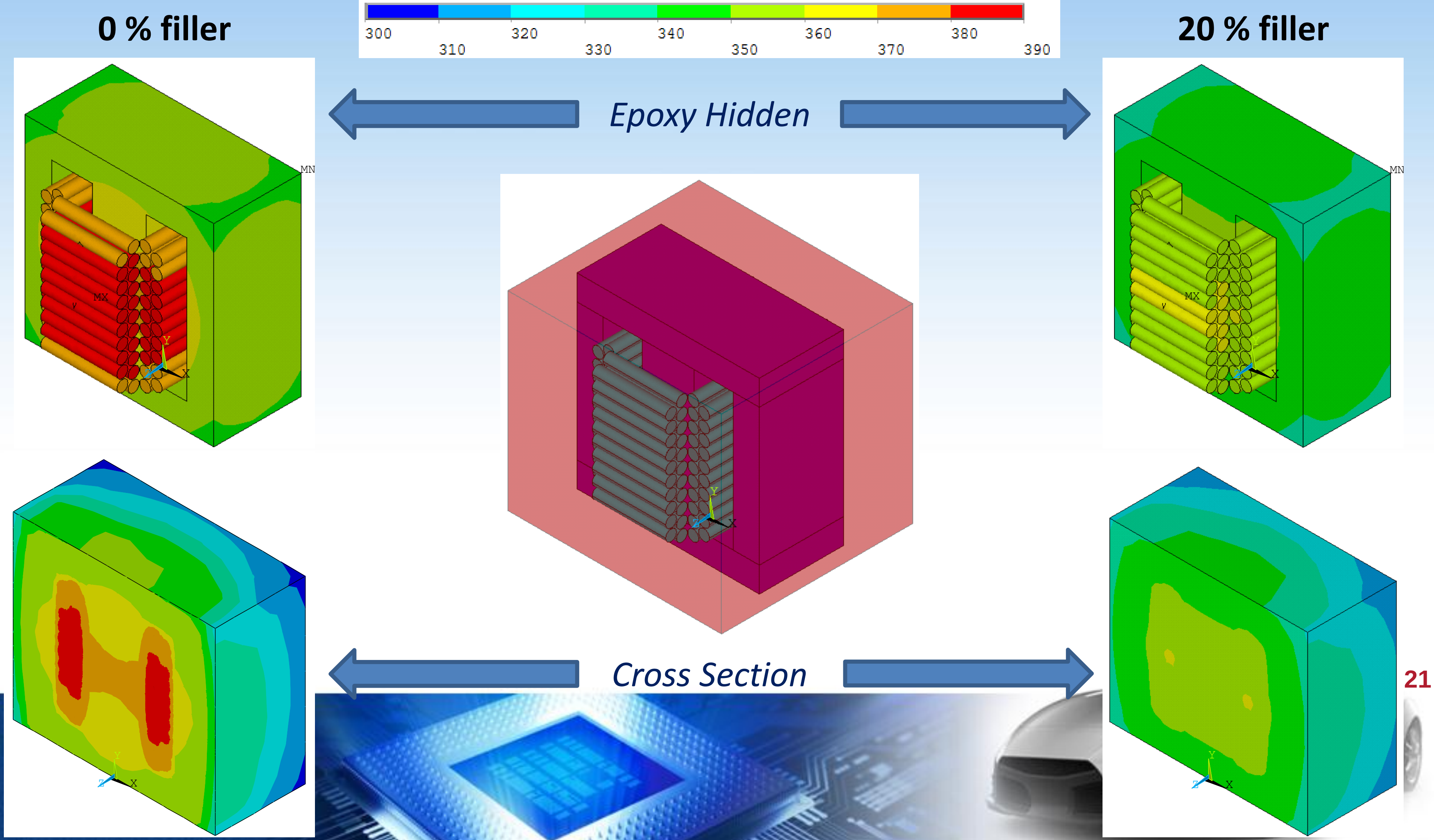
Effect of potting compound thermal conductivity

- Two potted inductors were manufactured
  - Standard Epoxy
  - Epoxy composite
    80 % Epoxy,
    20 % aluminium oxide
    (by volume)
- The inductors were tested at a range of power dissipations from 1 W to 10 W
- The steady state temperatures were recorded during testing



Finite element analysis modelling

- Finite element analysis model was produced for the inductor produced with standard epoxy



0 % filler

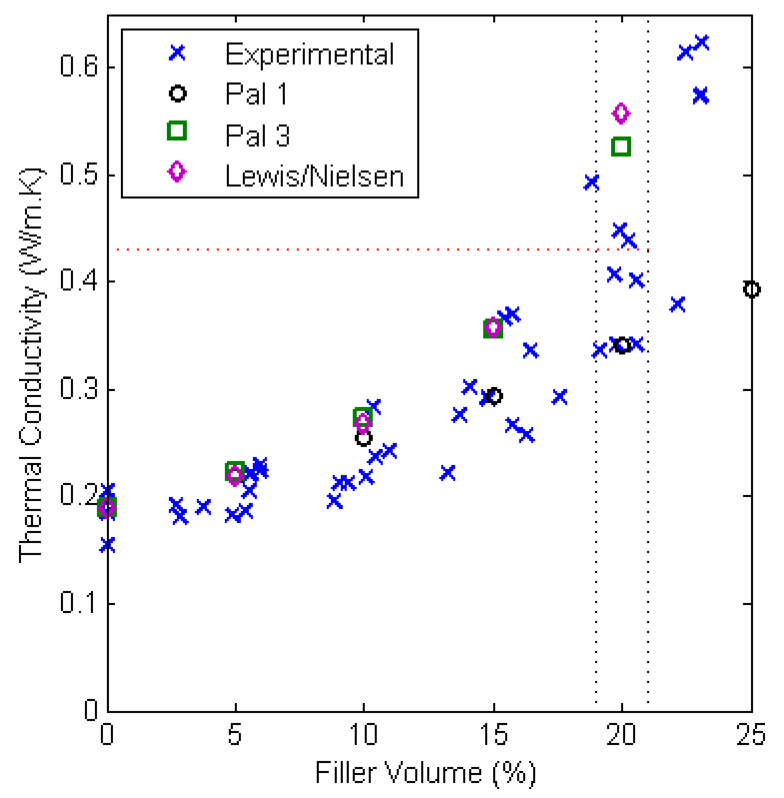
20 % filler

Epoxy Hidden

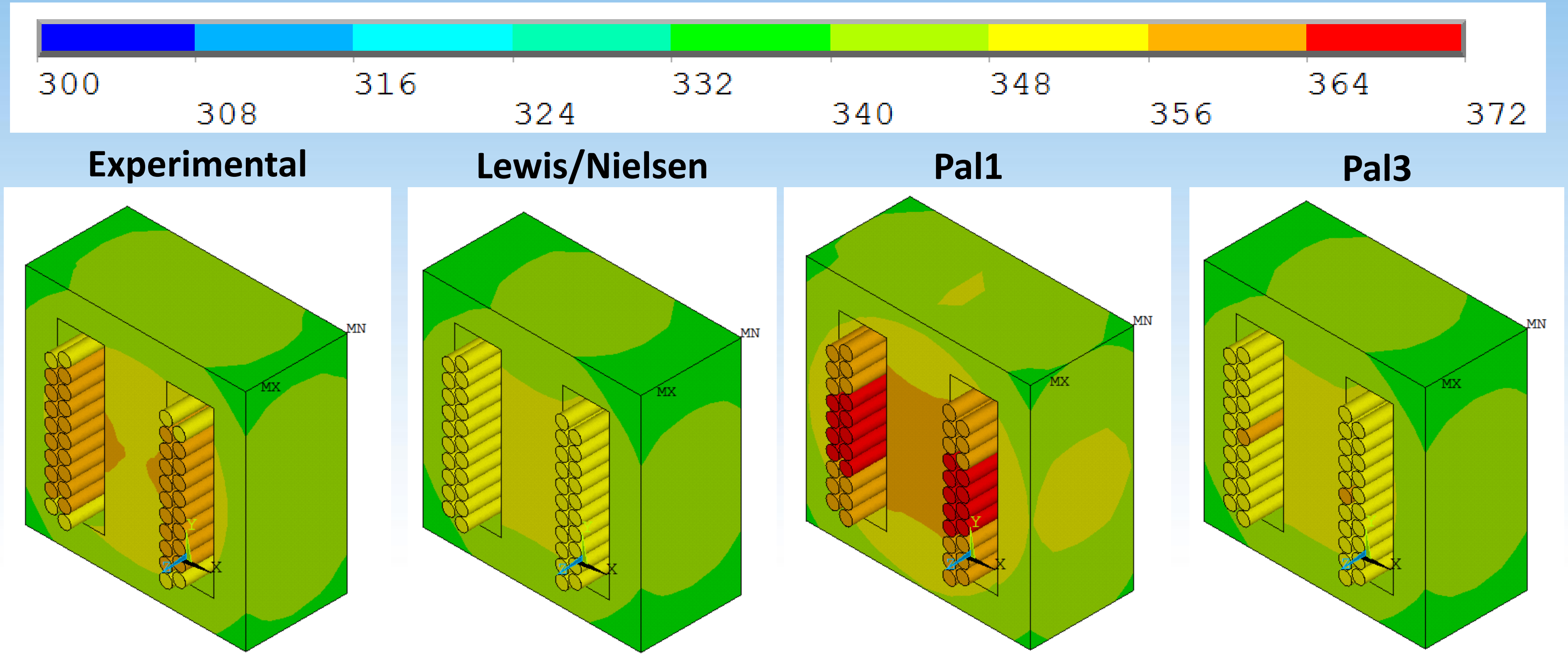
Cross Section

Determining bulk composite conductivity

- The FEA model was then used to determine the thermal conductivity of the composite potting compound
- This was achieved by adjusting the potting compound thermal conductivity the model matched the measured 20 % filled potting compound
- Thermal conductivity value was determined to be 0.43 W/m.K – this is within the values from the composite blocks (0.33 – 0.45 W/m.K)



Using analytical model values within FEA



Max Temp.	361.1	355.7	367.1	356.9
Difference	0	-5.4	6.0	-4.2
% Difference	0	-8.8 %	9.8 %	-6.9 %

Ambient temperature = 300 K

Conclusions

- The addition of thermally conductive filler materials to potting compounds results in improvements to thermal performance
- Analytical models can be used to obtain thermal conductivity predictions
- Using these values in finite element analysis yields temperature predictions within 10 % of experimental results (without prototype production)