Modelling the Enhancement to the Thermal Performance of Encapsulants using Thermally Conductive Filler Materials

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Abstract

This paper investigates the thermal conductivity of composite encapsulant materials that are produced by adding thermally conductive filler materials to potting compounds. To this end, prototype inductors have been manufactured and potted using both standard epoxy, and a filler/epoxy composite. A number of composite samples were created from which bulk thermal properties were extracted allowing thermal performance of the inductors to be predicted. Furthermore, the experimentally measured bulk thermal properties are compared with values obtained from several analytical models. Comparisons were made between temperatures experimentally obtained from the prototypes and finite element analysis models. It is found that using the values predicted by the analytical models, as well as composite samples allow a finite element model to predict the performance of the component within 10 % accuracy.

1. Introduction

Encapsulants are used in the construction of wound components for three principle purposes: i) sealing the component from the environment; ii) increasing the mechanical integrity of the component; and iii) improving the cooling of a component by displacing air trapped within the windings. It is possible to improve the thermal performance of encapsulants by employing composites which incorporate thermally conductive filler particles. It is necessary for the bulk thermal conductivity of this material to be easily modelled to allow predictions to be made about the thermal performance of the component using design tools, such as finite element analysis (FEA). The remainder of this paper is structured into several sections. Firstly, the available analytical models from literature are explored and compared to the performance of experimentally produced composite samples. Next, the production methods used to manufacture prototypes are explained, followed by details of the experimental procedures employed. The use of FEA is then discussed, including a study which considers the models sensitivity to bulk thermal conductivity values. Finally, consideration is given to the design of an inductor based on the methods explored in this paper.

1.1. Thermal conductivity of composite materials

The determination of the bulk thermal conductivity of composites is a subject which has been considered in literature [1, 2, 3, 4]. The first and simplest model considered here is the series model; more complex models such as those proposed by Maxwell [1]; Pal [2]; Lewis and Nielsen [3] are also explored.

The series model assumes that each constituent element of the composite is arranged into a solid, homogeneous block, arranged perpendicular to the direction of power flow; this simple model allows the thermal conductivity to be easily calculated however, its accuracy is poor, as a consequence of the oversimplification made regarding the structure of the filler material within the composite. The model proposed by Maxwell [1] overcomes some of these simplifications as it is derived for uniformly distributed spheres within a medium; here however, it is assumed that the spheres are well spaced, and as such, can be considered in isolation. While this is a valid assumption in the case of a composite with a low filler concentration, it becomes erroneous as the filler concentration is increased, due to the filler particles forming agglomerates; therefore, they can no longer be considered in isolation. This issue is addressed through the inclusion of additional parameters within the models to more accurately reflect the composite structure. In the case of Pal [2] three models are proposed, the first of which, does not include any additional parameters for composite structure. The other two models include a maximum filler concentration parameter, the inclusion of which permits the model to incorporate the effects of agglomerates. In Lewis and Nielsen's work [3] the maximum filler concentration is considered again, in this case an additional parameter, designed to reflect the shape of the filler particles is also incorporated; this extra parameter is particularly significant for filler particles which have a large difference between length and height. In the composites manufactured for this work the particles are approximately spherical, consequently this model achieves similar results to the models by Pal.

In this work composites produced from epoxy and aluminium oxide filler are considered. This composite consists of 80 % epoxy (by volume) and 20 % aluminium oxide filler. For these models, referring to Table 1, the bulk thermal conductivity value is predicted to be in the range of 0.24 W/m.K to 1.37 W/m.K, which is a very large spread of values. (Where the thermal conductivity of the epoxy is taken as 0.19 W/m.K; the aluminium is 30 W/m.K; and the maximum filler concentration is taken as 28%; these values are more fully justified in [4].)

An alternative method of determining the bulk thermal properties of the composite is to produce samples and experimentally measure the thermal conductivity [4]. Using this approach suggests that for a 20 % filler concentration a bulk thermal conductivity value in the range of 0.34 W/m.K to 0.45 W/m.K should be achieved for the materials used in this work; a much smaller range of values than that suggested by the analytical models.

Model	**Thermal Conductivity (W/m.K)**
Series	0.2371
Maxwell [1]	0.2604
Pal 1 [2]	0.3400
Pal 2 [2]	1.3740
Pal 3 [2]	0.5261
Lewis / Nielsen [3]	0.5574

Table 1 - Bulk thermal conductivity values obtained from analytical models

2. Production of prototype inductors

To compare the performance of standard epoxy encapsulant to that of the composite encapsulant, two inductors were manufactured and encapsulated. To prevent the entrapment of air within the epoxy during manufacture, the potting was performed within a vacuum chamber as shown in Fig. 1. The inductors used for these experiments are constructed with a pair of E42 ferrite cores, wound with litz wire; an example prior to potting is shown in Fig.

2(a); the standard and composite potted inductors can also be seen in this figure as parts (b) and (c) respectively.


(a) (b)

Fig. 1 Vacuum potting chamber used for component encapsulated: (a) – side cross-sectional view; (b) – top view of chamber

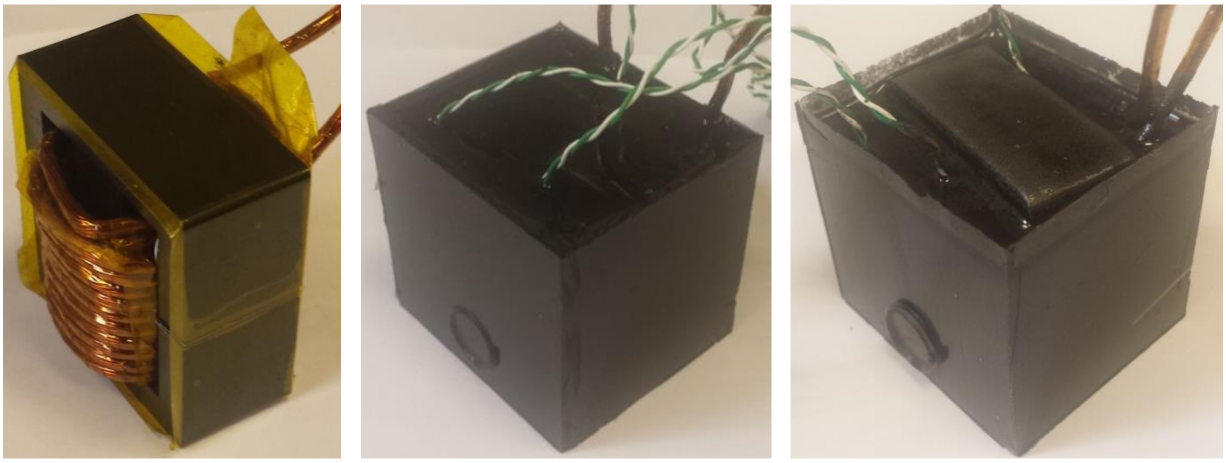

(a) (b) (c)

Fig. 2 Prototype inductors: (a) – prior to potting; (b) – Potted using standard potting compound; (c) – potted using potting compound composite (20 % fill)

3. Prototype evaluation

The thermal performance of the prototype inductors was evaluated by applying a fixed power dc excitation to the windings of each inductor. During this time the steady-state temperature rise within the inductor was monitored using thermocouples that were attached to the middle of the core centre leg and the middle of the windings prior to potting. During this test the component was cooled using natural convection in air in an ambient temperature of 23 °C. This experiment was repeated for both of the prototypes at a range of powers, to evaluate the performance of the components under a wide range of loads. The resultant steady state temperature increases are presented in Fig. 3. From this it can be observed that substituting standard epoxy for the thermally conductive composite results in a temperature reduction of at least 20 % at all power levels.

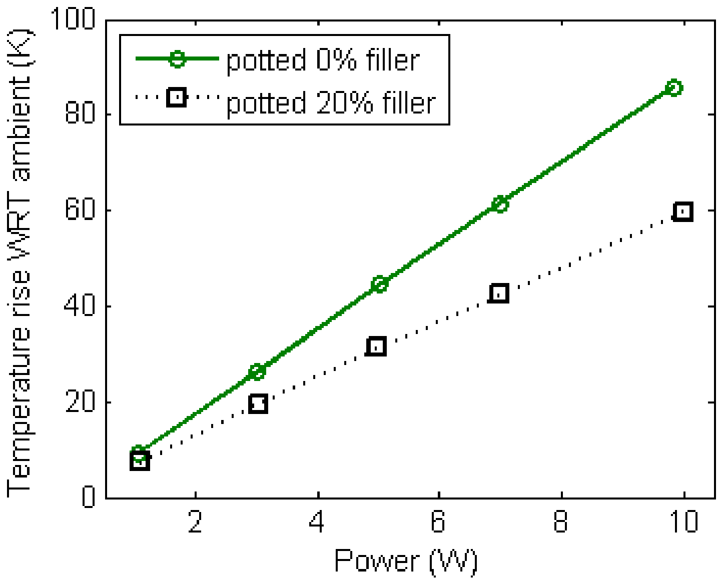


Fig. 3 Temperature increase of prototype inductors under dc excitation

4. Finite element analysis of prototypes

To determine the bulk properties of the potting compound composite a 3D FEA model of the inductor was produced. To validate the model it was configured using the data obtained from the standard potting compound inductor experiments. The FEA model exhibits good correlation with the experimental results; for example, when compared to the 10 W experimental results the winding temperatures show negligible differences and only a small difference (0.6 K) is present in the core temperature predictions, a result from the FEA simulation at a single power level can be seen in Fig. 4.

The bulk thermal conductivity of the composite encapsulant was then determined by empirically adjusting the thermal conductivity of the potting compound regions in the FEA model until the model temperature predictions conformed to the experimental results. In this case the bulk thermal conductivity was determined to be 0.43 W/m.K; which falls within the range of values predicted previously by both the analytical models and the composite samples.

The effect of varying the thermal conductivity of the potting compound regions on the FEA model predicted temperatures can be seen in Fig. 5. Here the predicted winding and core temperatures are shown plotted against the bulk thermal conductivity of the encapsulant regions in the model.

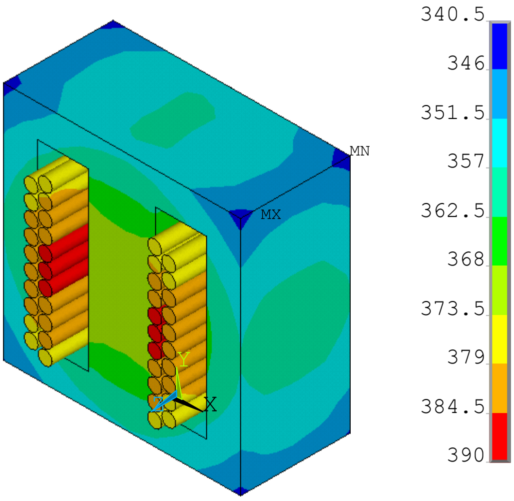


Fig. 4 Finite element analysis model of inductor potted using standard potting compound (Ambient temperature = 300 K) (Potting compound hidden)

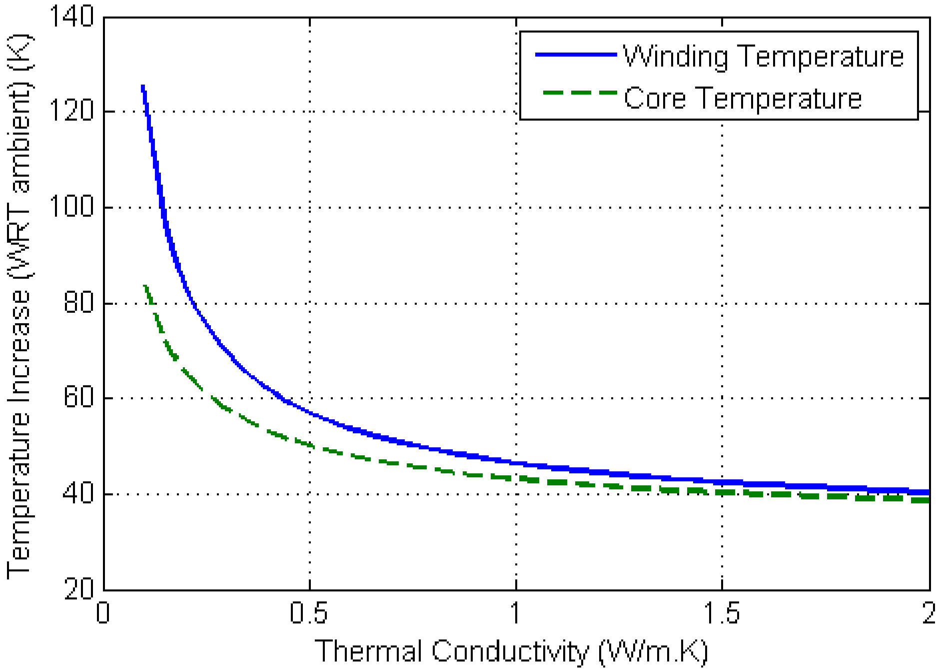


Fig. 5 Simulated temperature rise with respect to encapsulant thermal conductivity

4.1. Effects of composite thermal conductivity on FEA models

By varying the thermal conductivity of the encapsulant regions within the FEA models it can be observed that the operating temperature is highly non-linear with respect to the thermal conductivity; furthermore, the operating temperature approaches a limit as the thermal conductivity value is increased. While it may be possible to increase the thermal conductivity of the encapsulant beyond the values shown in Fig. 5, doing so would offer only marginal improvements to the component performance and so would be only be of limited value.

Considering this it is helpful to study how predictions from the FEA model are affected by the use of thermal conductivity values which deviate from the actual bulk value. Fig. 6 shows the FEA predicted winding temperature rise as a function of the composite bulk thermal conductivity. Values obtained from the analytical models, for a filler concentration of 20 % are highlighted on the curve; additionally, horizontal lines denoting the percentage deviation from the experimental reference result (red) are also included. From this investigation it can be seen that using the bulk properties obtained from three models: Pal 1; Pal 3; and the Lewis/Nielsen model all result in temperature predictions from the FEA model which lie within ±10 % of the experimental result and it can be concluded that it is possible to use these models in the component design phase to define a range of values in which the operating temperature will lie; this principle will be demonstrated in the next section of this paper.

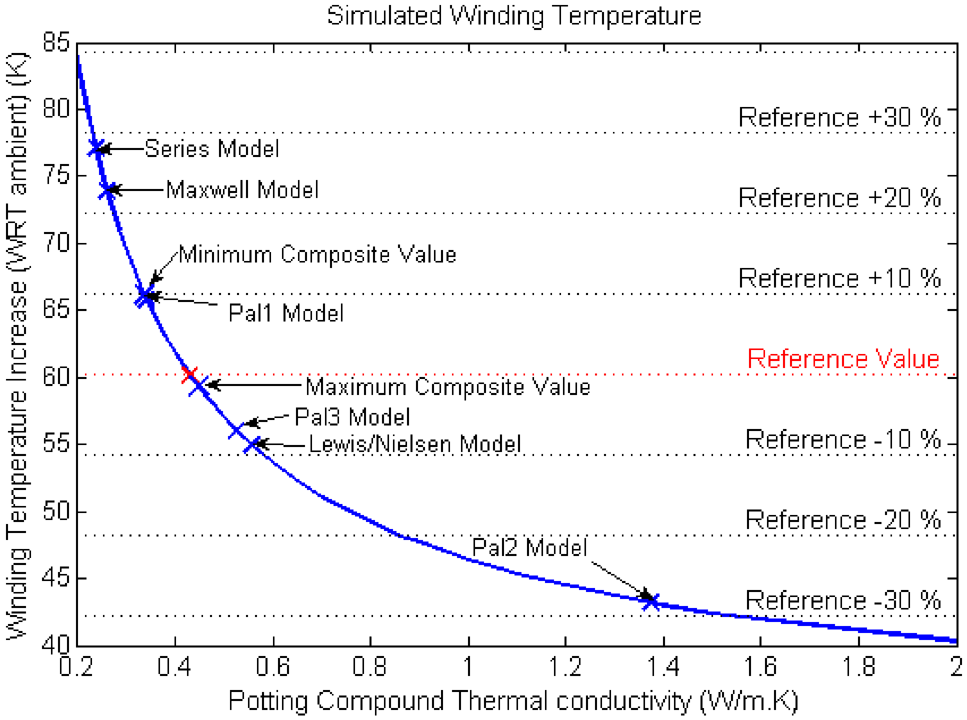
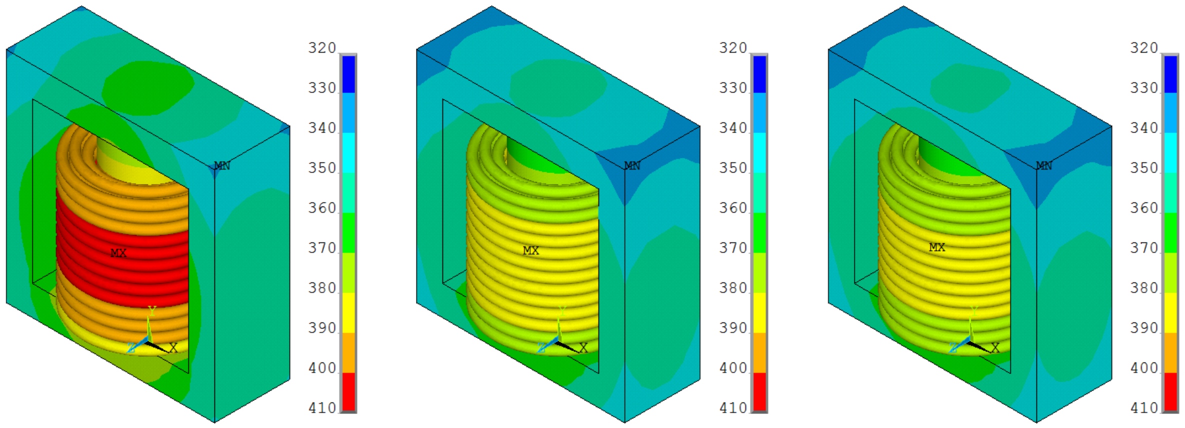


Fig. 6 Winding temperature predictions using thermal conductivity values from analytical models

5. Designing inductors using thermally conductive potting compounds

As previously stated, it is possible to predict the boundaries of the thermal performance of a component using the Pal1, Pal3 and Lewis/Nielsen models. This principle will be demonstrated through the design of a buck/boost inductor. This inductor was constructed using a pair of ETD 59 ferrite cores and was wound with litz wire. During the design process a FEA simulation model was constructed to predict the thermal performance of this component. The model utilised the bulk thermal conductivity values from the three analytical models highlighted previously, the results of these simulations using a 20 W power dissipation, can be observed in Fig. 7. Additionally, the predicted winding temperatures obtained from these simulations can be seen in Fig. 8 at a range of power dissipations.



(a) (b) (c)

Fig. 7 FEA model of designed inductor (Epoxy hidden) using bulk thermal conductivities from analytical models; 20 W power dissipation within windings: (a) - Pal 1; (b) – Pal 3; (c) – Lewis/Nielsen

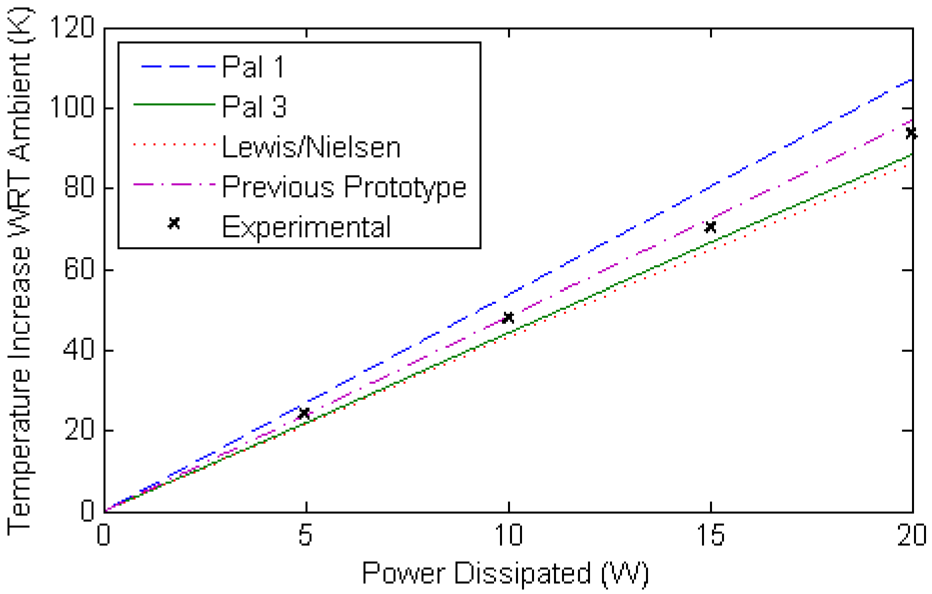


Fig. 8 Simulated operating temperature using analytically derived thermal conductivity values; compared to experimentally measured results

After using this FEA simulation to predict the operating temperature of the inductor a prototype was manufactured and tested using the same techniques as the previous prototypes. The experimental results obtained from the tests are included in Fig. 8. As expected, the experimental results fall within the boundaries obtained from simulations using the analytically obtained bulk parameters. Also plotted in this figure is a line showing the simulated temperature obtained using the bulk composite value achieved in the 20 % filler concentration prototype manufactured earlier in this work (0.43 W/m.K). It can be seen that the experimental results are close to this value. This is a useful observation as it demonstrates that the construction techniques (mixing of encapsulant and the fillings process) are consistent and repeatable between manufacturing runs. The deviation shown between the experimental results and the FEA prediction at higher power levels are likely to be a result of the assumption that convection is constant for all power levels; in reality this is not the case as convection coefficients are a function of temperature differential [5].

6. Conclusions

From the work presented here several conclusions can be drawn. Firstly, it is possible to utilise analytical models to predict the bulk properties of a composite. While these models produce a wide range of potential values for this property it is possible refine these predictions through the production and testing of composite samples, as demonstrated in [4]. By considering the effects of using these values within a FEA simulation it was found that the relationship between the bulk thermal conductivity of the encapsulant and the operating temperature is not linear; consequently, the use of a thermal conductivity value which has an error of 30 % can yield a temperature prediction within 10 % of the experimental results. Therefore, it is possible to design an inductor using these analytical values to predict the boundaries of the operating temperature. This technique is demonstrated within this paper and allows the range of the operating temperature to be determined prior to the construction of the component. This is supported by experimental measurements obtained from the prototype buck/boost inductor. These experimental results also demonstrate that the manufacturing technique utilised in this work provides consistent results; as demonstrated using the bulk thermal conductivity value from the first prototype within the buck/boost inductor finite element model. In this case a strong correlation between the simulated and experimental results can be observed.

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