THERMAL EFFECTIVE CONDUCTIVITY DETERMINATION FOR MULTI-LAYERED PRINTED CIRCUIT BOARDS FOR SPACE APPLICATIONS

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Abstract. *Electronic components are normally assembled to printed circuit boards – PCBs. Such components generate heat in operation which must be conducted away efficiently from the small areas to frames where PCB is fixed. The temperature of the components depends on heat dissipation rate, technology and parameters of mounting, component placement and finally effective conductivity of the PCB. The temperature of some components may reach significant magnitudes of order of ~100º C while the PCB frame is kept at near-ambient temperature. The reliability of electronic components is directly related to operating temperature; therefore the thermal project of PCB should provide correct temperature prediction of all PCB components under hottest operation condition. The PCB effective thermal conductivity is an important parameter having sensitive influence on component temperatures; its determination for complex multi-layer PCBs is not a trivial task. In space applications, the only way to spread and reject heat of electronic equipments is by thermal conduction once there is no air available to apply convection-based cooling systems such as heat sinks and fans. In this paper we present a survey on PCBs effective conductivity determination methods available in the literature as well as a simulation of a multi-layered PCB in order to compare the methods. The simulation uses a CAD based thermal model builder named SINDA/FLUINT Thermal Desktop and aims to determine the effective conductivity of a PCB by comparison between a detailed multi-layered anisotropic model and an equivalent homogeneous model. The model is validated using available data for two-layered FR4-copper PCB. Afterwards, simulations are performed for some PCB-frame configurations typical for space applications. The simulation outcomes are compared to the values of effective conductivity obtained by other methods. Besides, a sensitivity analysis is performed on variations in component mounting technology and PCB layers placement. Normal distribution of the effective conductivity is obtained for a 6 signal layers PCB. The results are discussed in a way of evaluation of applicability of existing methods and estimation of inherent uncertainty of PCB thermal effective conductivity determination.*

Keywords*: Effective conductivity, PCB, Space application*

1. INTRODUCTION

The overall trends in electronic equipment development for space applications are the miniaturization of electronic components, the increase of heat dissipation per component and density of component mounting in Printed Circuit Boards (PCB) and finally, the increase of PCB number in electronic equipment boxes.

Dissipated heat in each component causes its own temperature to rise. Depending on thermal conditions that the component is exposed, it may reach significant temperature of ~100º C while the PCB frame is kept at near-ambient temperature. Such high temperature exposure can damage electronic systems in different ways. First, the electronic components may simply be burnt-out once the functional temperature limit is exceeded. Second, component parameter values usually vary with temperature and it is important not to exceed the manufacture's temperature range defined as operational limits. Above such temperatures, the components are no longer guaranteed to be within specification, Carchia (1999). Finally, the reliability of electronic components is tremendously related to operating temperature, and according Remsburg (2001) component failure rate is increased exponentially with temperature rise even within the operational limits. Thus thermal project of the electronic equipment is an important aspect of a system's overall design, in order to ensure that the electronic components will not violate established temperature limits and will have their operational temperature as low as possible.

It underlines the importance of an accurate thermal analysis through the design process of electronics. Printed circuit board (PCB) is a basic element of electronic equipments, and a correct prediction of temperature distribution over its area provides the necessary information for temperature evaluation of each component mounted on the PCB. In space applications, the only way to spread and reject heat of electronic equipments is by thermal conduction over the board once there is no air available to apply the convection-based cooling systems.

In equipment and instruments for space application, PCBs are often assembled in a package where they are fitted through the perimeter to a structural frame. The frames are mounted in the equipment case in such a way that provides a good thermal contact with the equipment base, or thermal-mechanical interface. Finally, the equipment is bolted to satellite structural panel, which temperature should be maintained by the satellite thermal control subsystem.

The frame structure provides a thermal conductive path from dissipating components to the equipment base surface acting as a local heat sink for each PCB, therefore, the temperature distribution over the PCB area can be analyzed separately, considering fixed frame temperature as a boundary condition. Once we have the temperature map over PCB, particular temperatures of each component can be easily obtained by local thermal balance.

Temperature over the component mounting area is strongly dependent on its thermophysical properties. The PCB is usually manufactured in FR4 with thermal conductivity about 0.4 W/mK, what is considered to be low. However the conductive traces made of deposited copper contribute on in-plane thermal conductivity, assisting in heat spreading from hot areas below dissipating components. In the past PCBs used to have one or two signal layers, but nowadays modern technologies have allowed the production of complex PCBs that have several intermediate conductive layers. Such arrangement makes thermal properties of those PCBs strongly anisotropic.

The temperature map over the PCB can be obtained using numerical methods available through many commercial softwares such as ANSYS Iceboard (former TASPCB), HyperLynx Thermal (Former BETAsoft), FLOTHERM.PCB, SINDA/FLUINT Thermal Desktop, ESATAN and others, or even by analytical methods, Culham et al. (2000), Vlassov (2003)

However all of the methods are based on the supposition that the multi-layer PCB can be thermally represented by an equivalent homogeneous plate with certain effective thermal conductivity. It is suggested that such homogeneous plate with effective thermal conductivity calculated in a correct way, provides the same thermal effect as a real multi-layer PCB with anisotropic properties.

In this context, thermal modeling of heat conduction in multi-layer printed circuit boards is occasionally simplified by using the effective conductivity concept. Such parameter combines the influences of individual layer conductivities into a single value that can be applied as if the board had only one homogeneous layer where overall thickness and surface area are preserved. Some analytical methods have been proposed to calculate effective conductivity, where arithmetic mean, geometric mean and harmonic mean are among them. All of these methods are based on the cross-plane conductivity (series) and the in-plane conductivity (parallel) are generally considered to be the lower and upper limits for the effective conductivity respectively, and the difference between their values can reach 10 times. However, the published papers do not provide a clear definition how to calculate this value once the results are quite different between the lower and upper limits. This paper aims to contribute on how to evaluate the effective conductivity of a typical multilayer PCB for space application by direct numerical simulation.

2. EFFECTIVE CONDUCTIVITY DETERMINATION METHOD AND ITS VALIDATION

In order to estimate the effective conductivity of multi-layer boards we present a method based on numerical simulations which uses the CAD based thermal model builder SINDA/FLUINT Thermal Desktop.

The method consists of creating a conjugate pair of a complex and a simplified model that represent the same PCB layout and afterwards comparing them. The complex model is a multi-layer board wherein each of the layers has the same conductivity value as in the real PCB. Each signal layer with conductive traces is treated as a homogeneous layer with an equivalent conductivity equal to copper conductivity factored by percentage of covering area with electric conductive lines. The covering percentage was estimated visually based on a CAD design of the PCB.

On the other hand, the simplified model is a single-layer board, which thickness is obtained by summing the various layer thicknesses of the complex model, with a unique conductivity value called effective conductivity. The same boundary conditions and heat loads are applied both to the complex and simplified models.

Initially, we run the simulation for the complex model where the component (heat source) will reach certain temperature at the steady state. After that, we run several simulations for the simplified model modifying the board's conductivity until the component reaches the same temperature as in the complex model. Therefore, this conductivity can represent the effective conductivity of the complex model.

The basic approach of the method and model validation process was to reproduce the cases of study developed by Culham et al. (2000). Such study consisted of determining the effective conductivity of a 50 mm x 50 mm x 1.6501 mm board with 2 signal layers (copper – 400 W/mK) and 3 dielectric layers (FR4 – 0.4 W/mK). A 25 mm x 25 mm heat source was placed on the top surface, with 2.5 W of heat dissipation. A convective boundary condition of 5W/m^{2}K was imposed on the top and bottom surfaces (not on the heat source), which is a simplified representation of the natural convection cooling conditions in ambient air.

In that study, aiming to calculate the effective conductivity of the cases they have used a web tool which calculates based both on bulk material resistance and spreading resistance, using analytical solution.

The number and thickness of copper and FR4 layers were preserved but the layer placement was varied for 5 different test cases, as described in Tab. 1.

Table 1. Material and thickness for layer position study (dimensions in mm).

Layer	Case 1	Case 2	Case 3	Case 4	Case 5
1	Copper 0.0356	Copper 0.0356	FR4 0.5263	FR4 0.5263	FR4 0.5263
2	Copper 0.0356	FR4 0.5263	Copper 0.0356	Copper 0.0356	FR4 0.5263
3	FR4 0.5263	FR4 0.5263	FR4 0.5263	Copper 0.0356	FR4 0.5263
4	FR4 0.5263	FR4 0.5263	Copper 0.0356	FR4 0.5263	Copper 0.0356
5	FR4 0.5263	Copper 0.0356	FR4 0.5263	FR4 0.5263	Copper 0.0356

For the validation, the 5 test cases were reproduced using SINDA/FLUINT Thermal Desktop by applying the simulation method described above.

We created 2 models, a complex one (5 layers) and a simplified one (1 layer), applying the same conditions as described on the study. We have created a mesh of 10 x 10 x 2 edge nodes for the board in both models and kept the component as a single node. In Table 2 we can see the difference between the results of effective conductivity determined by the methods. Simplified and complex models are shown in Fig. 1 with the simulation results obtained by using SINDA/FLUINT Thermal Desktop for the first case.

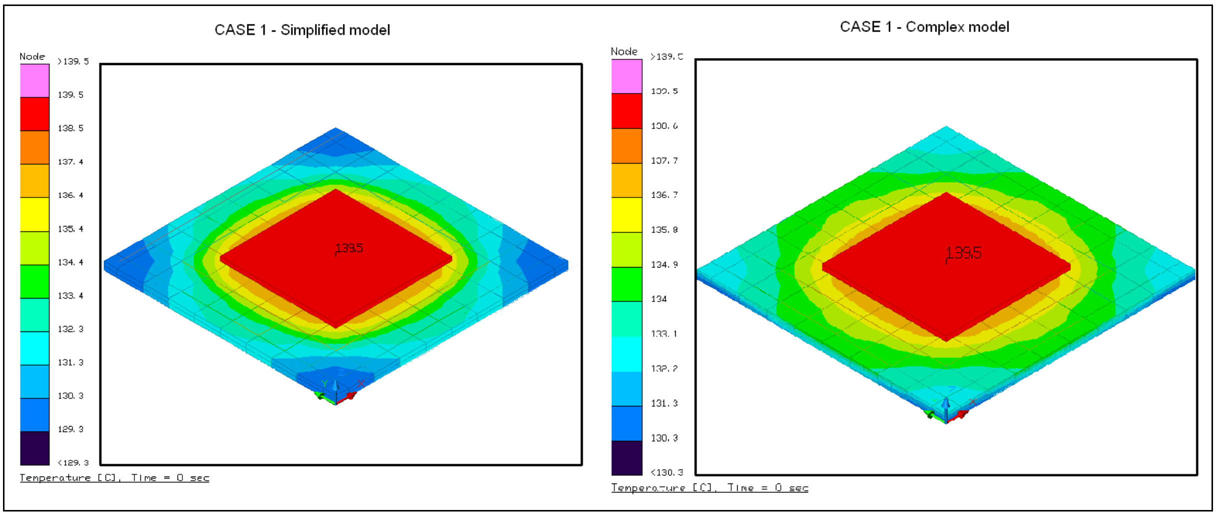

Figure 1. Simplified and complex models showing the temperature map obtained after the simulation.

As we can see in Tab. 2, there is a tendency of the values calculated by the simulation method to be lower than the values that had been calculated using the analytical method, but preserving almost the same variation and following the same decreasing order. We suppose the simulation method is more precise due to we used direct numerical simulation making no assumptions like in the analytical approach.

Table 2. Effective conductivities found by analytical and simulation methods.

Case	Analytical method results for effective conductivities (W/mK) (Culham et al., 2000)	Simulation method results for effective conductivities (W/mK)	Variation (%)
1	15	10.1	32.67
2	11.5	8.3	27.83
3	8.5	5.85	31.18
4	7.5	6.25	16.67
5	5	3.55	29.00

3. PCB FOR SPACE APPLICATIONS

The PCB sample used for the analysis was a 160 mm x 233.5 mm x 2 mm, consisted by 6 signal layers (conductive): top, GND, power, inner 1, inner 2 and bottom. Each layer has a certain percentage of copper and a fiberglass reinforced epoxy (FR4) is used as a dielectric material between layers; photographs of the PCB are shown in Fig. 2.

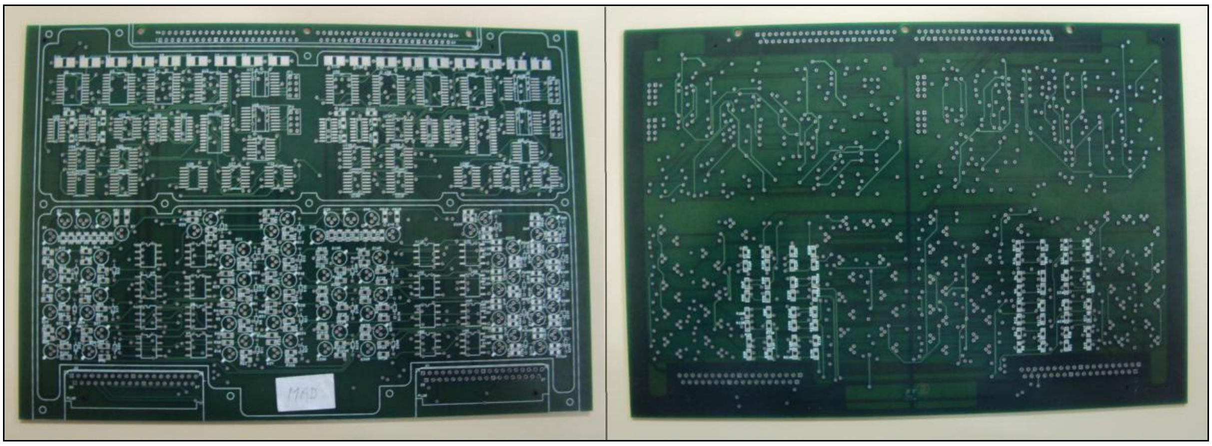

Figure 2. Multi-layered PCB for space applications (top/bottom photos).

From the board's project we can see the 6 signal layers in Fig. 3. We have estimated the copper coverage of each signal layer in order to apply a percentage factor over the copper conductivity in our model.

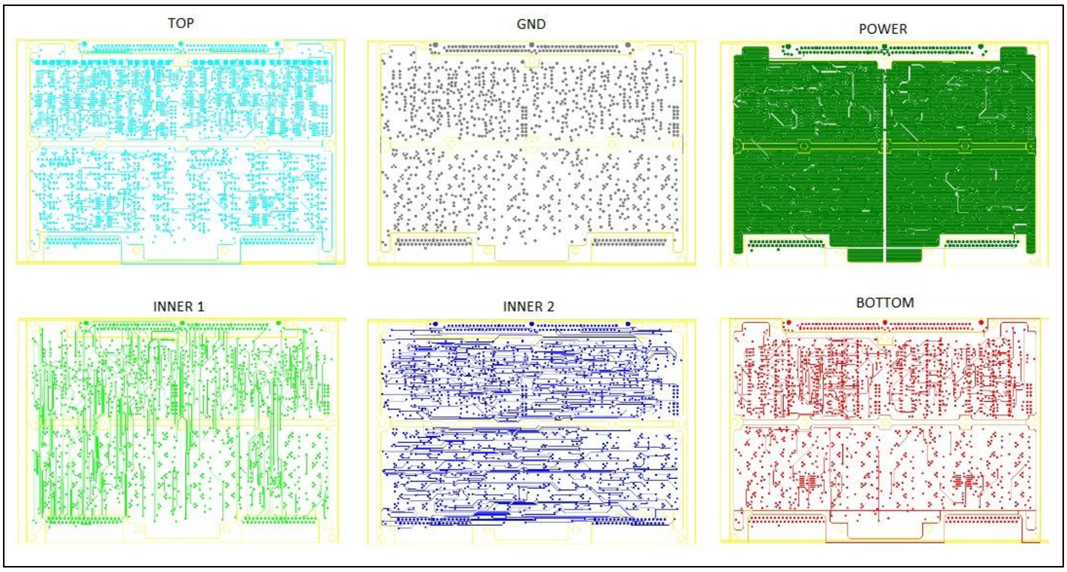

Figure 3. The 6 signal layers of the PCB.

As we had done previously, we created 2 equivalent models, a complex (11 layers) and a simplified (1 layer). The only boundary condition imposed to the model was a 10 mm wide frame kept at constant temperature of 20º C, which was placed at the bottom surface with heat transfer coefficient of 400 W/m^{2}K as contact condition. We tested several mesh configurations with gradual refining in order to get stable results that were achieved by setting 30 x 30 x 2 edge nodes for all board layers with 5000 W/m^{2}K for the contact between them. Tab. 3 shows the layer composition of the complex model, the signal layers with conductive lines were treated as a homogeneous layer with an equivalent conductivity equal to copper conductivity (400 W/mK) multiplied by the percentage of copper covering area, which was roughly estimated based on the PCB's project.

Table 3. Complex model composition.

LAYER	MATERIAL	THICKNESS (mm)	CONDUCTIVITY (W/mK)
1 – top	Copper (7%)	0.035	28
2 – dielectric	FR4	0.358	0.25
3 – GND	Copper (95%)	0.035	380
4 – dielectric	FR4	0.358	0.25
5 – power	Copper (2%)	0.035	8
6 – dielectric	FR4	0.358	0.25
7 – inner 1	Copper (6%)	0.035	24
8 – dielectric	FR4	0.358	0.25
9 – inner 2	Copper (8%)	0.035	32
10 – dielectric	FR4	0.358	0.25
11 – bottom	Copper (5%)	0.035	20

For the heat load, a 2 W dissipating component was created in 3 size configurations: 10 x 8 mm, 20 x 8 mm and 20x16 mm with 2500 W/m^{2}K for the contact with the top board surface. Such component was placed in 4 different positions as presented in Fig. 4. Two frames represented in the model as solid bars with fixed temperature are placed at left and right edges of the PCB.

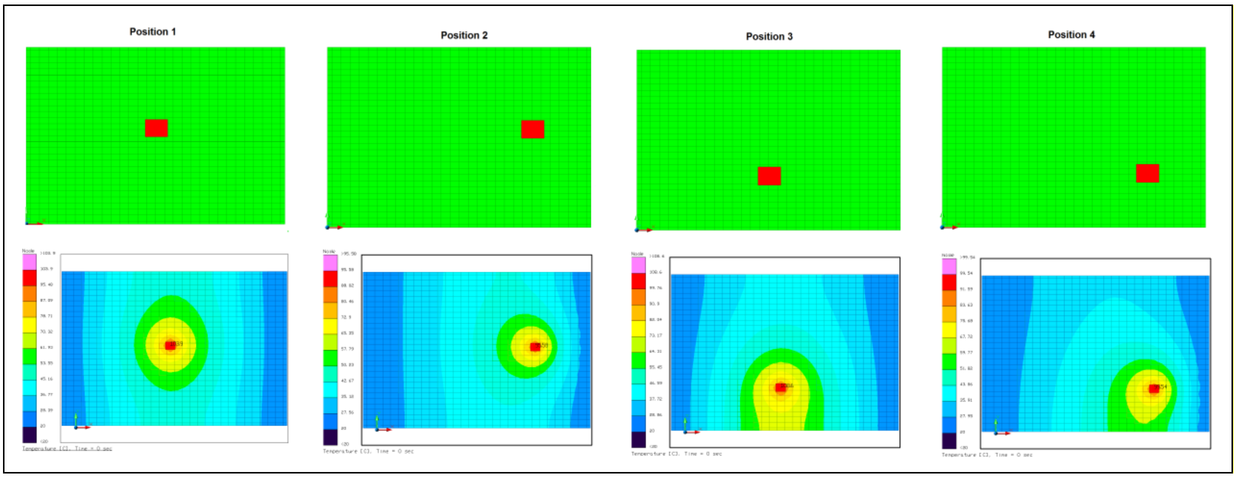

Figure 4. The 4 different locations for the dissipating component and the simulation results.

4. PCB MODEL AND UNCERTANTIES OF NUMERICAL SIMULATION

The SINDA/FLUINT Thermal Desktop tool performs numerical solution with afterward graphic representation of a system of energy conservation equation defined for the given PCB model. The core equation is 2D conductive heat transfer one applied along each PCB layer area, complicated with conjugate heat exchange with near-closest layers. In the domain of 11 layers depicted in Tab. 3, the system of equation can be presented as follows:

$$\delta_1 k_1 \frac{\partial^2 T_1(x,y)}{\partial x^2} + \delta_1 k_1 \frac{\partial^2 T_1(x,y)}{\partial y^2} + \sum_{j=1}^{N} g_{cj}(T_j - T_1(x,y)) + g_{1,2}(T_2(x,y) - T_1(x,y)) = 0 \tag{1}$$

...

$$\delta_i k_i \frac{\partial^2 T_i(x,y)}{\partial x^2} + \delta_i k_i \frac{\partial^2 T_i(x,y)}{\partial y^2} + g_{i,i+1}(T_{i+1}(x,y) - T_i(x,y)) + g_{i,i-1}(T_{i-1}(x,y) - T_i(x,y)) = 0 \tag{2}$$

....

$$\delta_{11}k_{11}\frac{\partial^2 T_{11}(x,y)}{\partial x^2}+\delta_{11}k_{11}\frac{\partial^2 T_{11}(x,y)}{\partial y^2}+g_{10,11}(T_{10}(x,y)-T_{11}(x,y))+g_{f,11}(T_f-T_{11}(x,y))=0 \quad (3)$$

Where: i runs 2 to 10;

j (1 to N) is the number of electronic component mounted on the top layer (for the Fig. 4 layout N=1);
g_{cj} – is the heat transfer coefficient between mounted component and PCB;
$g_{i,i+1}$ - is the heat transfer coefficient between internal PCM layers;
$g_{f,11}$ – is the heat transfer coefficient between frame and bottom PCM layer;
δ_I – is the thickness of i-th PCB layer
T_f – is fixed temperature of the frame where the PCB is mounted.

Along the PCB perimeter, the boundary conditions correspond to heat insulation conditions:

$$\frac{\partial T_i(x,y)}{\partial x}=\frac{\partial T_i(x,y)}{\partial y}=0 \qquad \text{- on PCB edges} \quad (4)$$

The system (1-3) is completed with local balances of component dissipations:

$$Q_j = A_j g_{cj}(T_j - T_1(x,y)) \quad (5)$$

Where A_j is the area of the j-th component.

In general case the system (1-4) can be presented as 3D system considering that each layer can de divided in sub-layer in orthogonal, i.e. z-direction.

Several numerical examinations were carried out in order to define optimal numerical mesh size and correct numerical representation of the PCM layout. We followed general approach based on gradual refining of numerical mesh until the solution becomes invariant to further reductions in grid spacing. By this way we achieved the numerical mesh of 30x30x2 for each layer. During the examinations we observed several numerical effects which could cause distortional results if treated incorrectly. Besides, numerical tests were also performed in order to ensure that the numerical parameters do not affect the accuracy of the model. The main observations are listed below.

- SINDA Thermal Desktop tool may use two types of mesh – center or edge nodes, which correspond to finite differences or finite elements respectively. In the case of plane rectangular elements it corresponds either to center node with uniform temperature over the numerical cell (FD) or 4 temperatures for each corner of the cell (FE). In the numerical test no outcome differences were observed by switching FD and FE mesh types.
- For the validation model mesh: 2 nodes in z direction were needed to satisfying results; no problems regarding the component placement;
- Still for the validation model: once the component had a great area and was treated as a single node, the nodes just below the component may be artificially linked, in order to avoid it we tried to refine the component's mesh in addition to setting a low conductivity property for the component's material - no differences were observed.
- For our sample PCBS we had to set a mesh of 30x30x2 edge nodes for all layers and component in order to obtain stable results;
- No different outcomes were found by simply changing the component's dissipating power;
- We also had problems regarding results instability because the component had a small size in comparison to the board (the component was too small to the mesh, which could not be more refined because of numerical limitations). We had to place the component in order that it covers a whole node.
- Contact resistance was not well known, so we tried different values, starting from high value as 20000 W/m^{2}K and approaching lower values when the effect of artificial conductance is eliminated, the value of 5000 W/m^{2}K was assumed;
- Each layer should be presented by the numerical mesh with the same size and number of elements. Otherwise, the effect of artificial conductivity may disturb the results.

5. RESULTS AND DISCUSSIONS

Several analytical simplified methods have been proposed for calculating effective conductivity of multi-layer boards, including the cross-plane conductivity and the in-plane conductivity see Fig. 5 (Culham et al., 2000). The application these methods to the PCB under investigation yields results presented in Tab. 4.

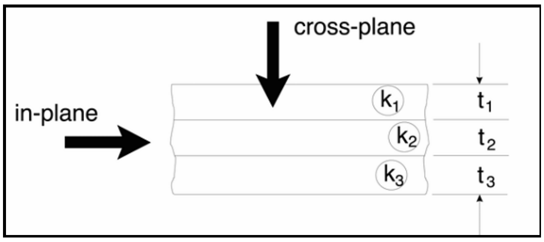

Figure 5. Basic conductivity definition in laminated substrate.

Table 4. Calculated values of the PCB effective conductivity by simplified methods

METHOD	CONDUCTIVITY (W/mK)
In-plane	8.8337
Cross-plane	0.2789
Arithmetic mean	4.5563
Geometric mean	0.6370
Harmonic mean	0.5408

In order to demonstrate the importance of the effective conductivity on PCBs and better understand how it affects the component's temperature, we made a test applied each of the results in Tab. 4 in our simplified model; the component reached a different temperature for each value, see Tab. 5. The temperature using the complex model was 103.9º C.

Table 5. Simplified model temperature applying the values of effective conductivities found with the analytical methods.

METHOD	TEMPERATURE (º C)
In-plane	100.3
Cross-plane	1945.0
Arithmetic mean	160.9
Geometric mean	887.0
Harmonic mean	1035.0

In spite of some magnitudes given in Tab. 5 are far from reality, such dramatic difference just empathize the importance of precise calculation of the effective thermal conductivity.

After performing the simulation for the 4 different positions (Fig. 4), changing 3 times the component size and applying our method described above, we came up with the results for the effective conductivity in the PCB, see Fig.6.

Table 6. Simulation outcomes.

POSITION	COMPONENT SIZE (mm)	COMPONENT'S TEMPERATURE (º C)	EFFECTIVE CONDUCTIVITY (W/mK)
1	0.01x0.008	103.90	8.380
	0.02x0.008	92.96	8.003
	0.02x0.016	87.10	7.814
2	0.01x0.008	95.58	7.864
	0.02x0.008	82.03	7.440
	0.02x0.016	75.92	7.187
3	0.01x0.008	108.60	8.400
	0.02x0.008	97.61	8.053
	0.02x0.016	90.54	7.868
4	0.01x0.008	99.54	7.845
	0.02x0.008	85.72	7.428
	0.02x0.016	78.59	7.195

By using the effective conductivities presented in Tab.6, we calculated a mean of 7.7897 W/mK with 0.4069 of standard deviation. Afterwards, a normal distribution curve was drawn as shown in Fig. 6.

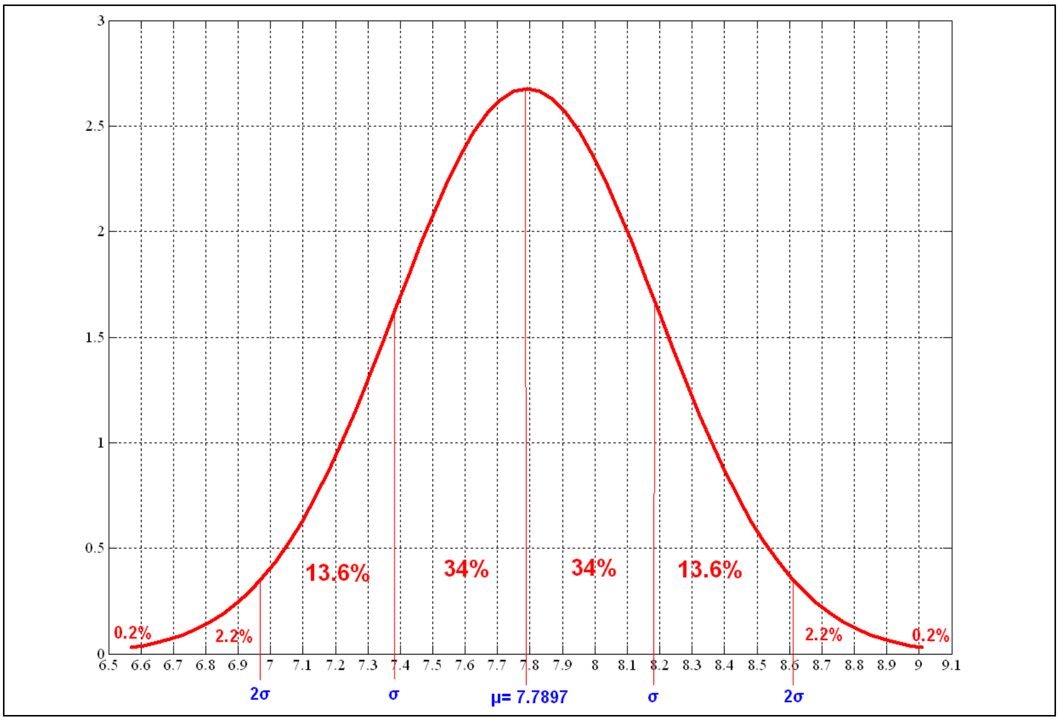

Figure 6. Normal distribution for the effective conductivity.

The value of 7.7897 W/mK was expected once it is between the in-plane and the cross-plane values, which are considered the upper and the lower limits for the effective conductivity respectively. The chart presented in Fig. 6 shows the probability of each value around the mean based on our data.

6. CONCLUSIONS

The PCB effective thermal conductivity was obtained by direct simulation used the CAD based thermal model tool SINDA/FLUINT Thermal Desktop. The method was validated by comparison with the published results obtained by more-simplified analytical model; deviation was within ~30% and tendencies have been confirmed for all combinations of layer placements. For the real 6-layer PCB the average value is 7.7897 W/mK, that lies between the limits of the in-plane and arithmetic mean simplified analytical models. The important result is that the uncertainty in the effective thermal conductivity definition for the given example lies between 6.98 to 8.61 W/mK within 95% confidence interval, because of the variety in the component size and positioning. This yields an important practical conclusion: even theoretically, the uncertainty of the PCB effective thermal conductivity will not be greater than ±11%; and this variation should be accounted in the thermal project of electronic equipment. Particularly, for the dissipating component, used in the present numerical simulation, this uncertainty corresponds to an uncertainty up to ±10º in terms of the component temperature value within the same 95% confidence interval.

For future work, more simulation cases will be needed to better understanding how the effective conductivity behaves along the board and to have more data, which would allow us to statistically analyze the effective conductivity on multi-layer boards with higher accuracy. The experimental validation of the present method is also under way.

7. ACKNOWLEDGEMENTS

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