Evaluation of 1-D & 2-D models for thermal insulation thickness calculation in electronic packaging

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Keywords: resistance network analysis, orthotropic material, heat spreading, numerical modeling, electronic packaging, multi-chip module (MCM)

ABSTRACT: The objective of this study is to evaluate the use of 1-D and 2-D compact heat transfer models for thermal design, optimization, and performance evaluation in electronic packaging. A model for heat spreading in orthotropic materials is developed. A resistance network analysis for calculation of heat transfer rate and junction temperatures has been carried out. A refrigeration cooled server package is used to illustrate the methodology. Heat transfer in the package components is modeled. Results of the analytical model and resistance network analysis are compared with a numerical solution. Capability of the analytical model in predicting the thermal field is discussed, and the effectiveness of using 1-D and 2-D models in thermal design and optimization of electronic packages is demonstrated.

1 NOMENCLATURE

- \( a \) Radius of circular source, [m]
- \( A_{PCB} \) Printed circuit board area, \([m^2]\)
- \( A_{MP} \) Module projected area, \([m^2]\)
- \( b \) Heat spreading distance, [m]
- \( h \) Convective heat transfer coefficient, \([W/m^2\cdot C]\)
- \( H \) A dimensionless factor found from Kennedy chart
- \( k \) Thermal conductivity, \([W/m \cdot C]\)
- \( k_a \) Axial thermal conductivity, \([W/m \cdot C]\)
- \( k_r \) Radial thermal conductivity, \([W/m \cdot C]\)
- \( l \) Rectangle side length, [m]
- \( P \) Evaporator cooling capacity, [W]
- \( Q \) Chip total heat dissipation, [W]
- \( q \) Heat transfer rate, [W]
- \( r \) Radial coordinate, [m]
- \( R \) Spreading resistance, [C/W]
- \( t \) PCB thickness, [m]
- \( T \) Temperature, [C]
- \( T_1 \) Circular source temperature; top insulation temperature, [C]
- \( T_2 \) Side and base temperature of cylindrical model; Back insulation temperature, [C]
- \( T_3 \) Board temperature at the outer edge of the module, [C]
- \( T_\infty \) Ambient temperature, [C]
- \( T_{base} \) Base temperature of circular fin, [C]
- \( T_{mean} \) Circular fin mean temperature [C]
- \( T(r) \) Circular fin radial temperature [C]
2 INTRODUCTION

Providing a three-dimensional model for thermal and flow fields in electronic systems is time consuming, especially for early stages of design when the geometric parameters are being optimized. For quick estimate of the heat flow paths and junction temperatures in electronic packages, the concept of thermal resistance networks is commonly employed (e.g. Guenin et al. (1995)). Other authors have provided alternate modeling methodologies. Nigen (1992) has developed a thermal methodology for printed circuit boards (PCBs) in order to roughly analyse a conjugate conduction/convection problem. Furmanczyk (1998), and Franke (1999) provided similar models for thermal analysis of electronic components. Three issues of primary concern in these models are:
- Heat spreading from heat source through orthotropic media such as ceramic substrates and printed circuit boards containing layers of metallization;
- Simulation of individual heat sources on substrates;
- Modeling of board and ambient heat exchange.

A number of studies have addressed various aspects of these issues (e.g. Culham et al. (1998, 2000), Huang et al. (1993), Lemczyk et al. (1988), and Teertstra (1997)). The current study provides a model for multi-chip modules (MCMs) thermal design and optimization. In the following the details of the heat transfer model is given first, followed by a case study that demonstrates its application to a refrigeration cooled server package.

2.1 Heat spreading in homogeneous and orthotropic materials

Heat spreading in electronic packages refers to multi-dimensional conduction that occurs when two regions with different heat transfer cross-section areas, are in contact. A common example is the case where heat is conducted from a chip through a substrate or a PCB. Several closed form solutions have been provided to model the spreading resistance (Cooper et al. (1969), Kennedy (1959), and Lee et al. (1995)) in simplified configurations. These analytical solutions are generally restricted to homogenous, isotropic-materials. Electronic packaging structures are often anisotropic. For example, the presence of metallization layers within substrates makes the in-plane conduction properties very different from out-of-plane.

Kennedy (1959) obtained the thermal resistance for a circular discrete, uniform surface heat flux source of radius a, placed at the center of a cylinder b of a homogeneous material ($K_z = K_r=1$) as:

$$ R = \frac{H}{a\pi} $$

(1)
Where $H$, a function of $a/b$ and $w/b$ (Fig. 1), is available in closed form, and also available as the Kennedy charts (Tummala et al.). In the following, a transformation is used to extend the Kennedy solution to orthotropic materials:

$$ r^* = \frac{r}{\sqrt{k_r}} , \quad z^* = \frac{z}{\sqrt{k_z}} $$  \hspace{1cm} (2)

Where $r^*$ and $z^*$ are transformed coordinates. To show the applicability of this transformation, consider the heat conduction equation in an orthotropic material in cylindrical coordinates:

$$ \frac{\partial}{\partial z^*} (k_z^* \frac{\partial T}{\partial z^*}) + \frac{1}{r^*} \frac{\partial}{\partial r^*} (k_r^* r^* \frac{\partial T}{\partial r^*}) = 0 \hspace{1cm} (3) $$

Using the above transformation, Equation 3 reduces to:

$$ \frac{\partial}{\partial z} (k_z \frac{\partial T}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial r} (k_r r \frac{\partial T}{\partial r}) = 0 $$ \hspace{1cm} (4)

Boundary conditions are transformed accordingly. For example, for the top circular heat source in figure 1, the transformed form of boundary condition is:

$$ z^* = 0, \quad 0 < r^* < a^* \quad T = T_1 $$ \hspace{1cm} (5)

Where $a^*$ is the transformed radius of circular heat source given by:

$$ a^* = \frac{a}{\sqrt{k_r}} \hspace{1cm} (6) $$

This transformation enables us to use the Kennedy solution in the transformed domain. The transformed thermal resistance can be determined as follows:

$$ R^* = \frac{T_1 - T_2}{q^*} = \frac{H^*}{\pi a^*} \hspace{1cm} (7) $$

Where $H^*$ is a function of $a^*/b^*$ and $w^*/b^*$. The following expression gives the heat transfer rate through the circular source in transformed domain:

$$ q^* = \int_0^{a^*} \frac{\partial T}{\partial z^*} 2\pi r^* \, dr^* $$ \hspace{1cm} (8)

While the actual heat transfer rate, $q$, is given by:

$$ q = \int_0^a k_z \frac{\partial T}{\partial z} 2\pi r \, dr $$ \hspace{1cm} (9)

Using Equations 2, 8, and 9, the relation between actual heat flux and transformed heat flux can be determined.

$$ q = k_r \sqrt{k_z} q^* $$ \hspace{1cm} (10)

Therefore, the relation between the actual thermal resistance, $R$, and the transformed thermal resistance, $R^*$, can be found as follows:

$$ R = \frac{T_1 - T_2}{q} = \frac{1}{\sqrt{k_z k_r}} \frac{T_1 - T_2}{q^*} $$ \hspace{1cm} (11)

Evaluation of 1-D & 2-D models for thermal insulation thickness calculation in electronic packaging
Equation 11 implies the following relations between actual and transformed thermal resistances.

\[ R = \frac{1}{\sqrt{k_1/k_r}} R^* \]  
\[ R = \frac{H^*}{\pi \sqrt{k_1/k_r} a} \]  

2.2 Printed circuit board and ambient heat exchange

The extended portion of the printed circuit board (PCB) has been simulated as a circular fin. The following equations determine the equivalent internal and external radius of this circular fin that extends out of the module corners.

\[ r_o = \sqrt{\frac{A_{PCB}}{\pi}}, \quad r_i = \sqrt{\frac{A_{SP}}{\pi}} \]  

Using this simplified geometry, total thermal resistance of the fin and its surrounding ambient has been determined using Bessel’s solution for a circular fin with convection boundary conditions (Guenin 1995):

\[ T(r) - T_\infty = (T_{base} - T_\infty) \frac{K_i(Mr)I_0(Mr) + I_1(Mr)K_0(Mr)}{K_i(Mr)I_0(Mr) + I_1(Mr)K_0(Mr)} \]  

Where \( M \) is defined as follows:

\[ M = \sqrt{\frac{2h}{kt}} \]  

By integrating for heat dissipation over the surface, using Equation 15 for local temperature difference, the following expression for the thermal resistance from module to ambient yields:

\[ R = \left( \frac{1}{2\pi r_i M} \right) \frac{K_i(Mr)I_0(Mr) + I_1(Mr)K_0(Mr)}{K_i(Mr)I_0(Mr) + I_1(Mr)K_0(Mr)} \]  

The mean temperature of the PCB is calculated using the following equation:

\[ T_{mean} - T_\infty = \frac{\int (T(r) - T_\infty) 2\pi r dr}{2\pi (r_o^2 - r_i^2)} \]  

\[ T_{mean} = T_\infty + \frac{2\pi (T_i - T_\infty) \left[ K_i(Mr)I_0(Mr) + I_1(Mr)K_0(Mr) \right]}{M(r_o^2 - r_i^2)} \]  

Flow is assumed to be laminar over the board and the natural convection heat transfer coefficient at constant wall temperature has been used in the above equations.

In order to find an appropriate magnitude of \( T_{mean} \), a trial and error procedure has been employed. This model, along with thermal resistances for the other components that are available analytically, can be used to complete the thermal resistance network for a MCM module. An example to apply this is presented below.
3 EVALUATION OF THE DEVELOPED MODEL

In order to evaluate the developed model for MCMs’ thermal analysis, a refrigeration cooled multi-chip module of an IBM CMOS Server has been considered (http://www.electronics-cooling.com/html/2000_sep_a1.html). Figure 2 shows the details of the package, in which chips have been simulated as uniform heat sources. The specifications of the components are given in Table-1.

The objective of this thermal modeling is to simplify the design procedure of a condensation free package. In order to avoid the condensation, insulation has been used on the outer surface of the evaporator/module, as well as on the board’s backside. Operating ambient conditions dictate a minimum surface temperature of 21 °C (ambient dew point).

4 RESISTANCE NETWORK

A thermal resistance network, to analyze the system temperature and cooling power consumption, as a function of insulation thickness, is presented in Figure 3. Three design options were analyzed. First, a minimum insulation thickness of 3 mm was considered for the entire module as well as the backside of the board. The analysis was repeated for the second design option with 20 mm for the insulation thickness. In the third option, insulation thickness on the module was 20 mm and was 3 mm on the backside of the board. The results of the resistance network solution for temperature and cooling power consumption are given in Table 2.

5 NUMERICAL MODELING

A numerical solution is provided to evaluate the results of the analytical model. IcePak software (Fluent, Inc. & ICEM-CFD Engineering – Lebanon, NH) was used as the numerical solver. First, in order to verify the grid size independency of the results, airflow over the board with constant temperature was modeled numerically. The result was compared with the similarity solution for laminar flow natural convection along a vertical plate.

The circuit board with dimensions 56.0 (W) × 45.7 (H) × 0.6 (t) cm³ was simulated as a cold vertical plate in IcePak software. The plate and ambient temperatures were set at 17.68ºC and 35ºC, respectively. Two solutions have been prepared in order to study the effect of the grid size on the numerical solution and the results were compared with the similarity solution. The result shows an error of 3.26 percent for the coarse mesh and 2.83 percent for the fine mesh.

In the second step the entire module and board were simulated. The evaporator was modeled as a high thermal conductivity block. A numerical grid structure with 294694 nodes was generated in the cabinet that contains the module and board assembly. Figure 4 demonstrates this configuration. The numerical solution was provided for the third design option. Using the data given in Table 3 the evaporator cooling capacity was adjusted to 934.32 W while the total heat generation rate was 925 W and the ambient temperature was 35 ºC. The results of the numerical solution are presented in Figure 5.

5.1 Numerical results

The evaporator has an average temperature of 10.13 °C and its minimum temperature is 9.79 °C. The chip average temperature is 16.66 °C. The maximum temperature is found on the top corners of the board and is about 34 ºC. Figure 5 shows the temperature contour in a cut plane of the entire module assembly. As we can see, the temperature field from the evaporator to the chips and substrate is more or less one-dimensional. The most deviation from the one-dimensional aspects occurs on the top insulation, where the temperature varies from about 24 ºC on the top corner (Point
"A") to 18 °C at the center (Point "B"). The average temperature of the top insulation is about 21.34 °C. These results show that condensation will take place at the center of the top insulation. The temperature variation in the back insulation is rather small and its mean value is 26.6 °C, which is above the dew point.

Figure 1. Schematic of the model

Figure 2. Multichip module (MCM) configuration
$R_1$: Resistance between chip and substrate  
$R_2$: Substrate resistance  
$R_3$: Resistance from substrate to the board  
$R_4$: Board spreading resistance from resistance $R_3$ to the end of the module  
$R_5$: Board perpendicular resistance  
$R_6$: Insulation resistance at the back of the board  
$R_7$: Convective resistance between the board back insulation and the ambient  
$R_8$: Resistance from module to ambient, through the board (includes both the conductive and convective resistances)  
$R_9$: Resistance from the chip to the hat  
$R_{10}$: Hat thermal resistance  
$R_{11,i}$: Top insulation resistance (index “i” represents the five different sides of the top insulation)  
$R_{12,i}$: Average convection resistance from insulation to the ambient (index “i” represents the five different convection heat transfer coefficient on different sides of the top insulation)  
$R_{13}$: Resistance between hat and evaporator  
$P$: Evaporator cooling capacity  
$Q_{\text{chips}}$: Chips’ total heat dissipation

Figure 3. Resistance network for the module and board

Figure 4. Numerical results for the Module/Board in natural convection
Figure 5. Temperature distribution in module/board and air

Table 1. Module components specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip</td>
<td>Chip size</td>
<td>15 mm square x 0.38 mm thick</td>
</tr>
<tr>
<td></td>
<td>Power/chip</td>
<td>25×37 watts</td>
</tr>
<tr>
<td></td>
<td>Chip spacing (center to center)</td>
<td>23 mm</td>
</tr>
<tr>
<td></td>
<td>Resistance between chip and hat</td>
<td>0.20 C/W</td>
</tr>
<tr>
<td></td>
<td>Resistance between chip and substrate</td>
<td>0.18 C/W</td>
</tr>
<tr>
<td>Substrate</td>
<td>Substrate size</td>
<td>127 mm square x 5 mm</td>
</tr>
<tr>
<td></td>
<td>Substrate thermal conductivity</td>
<td>0.0038 W/C-mm</td>
</tr>
<tr>
<td></td>
<td>Resistance between substrate and board</td>
<td>0.7 C/W</td>
</tr>
<tr>
<td></td>
<td>Distance between substrate and board</td>
<td>2 mm</td>
</tr>
<tr>
<td>Module</td>
<td>Module hat thickness</td>
<td>11.8 mm</td>
</tr>
<tr>
<td></td>
<td>Module hat material</td>
<td>Pure copper</td>
</tr>
<tr>
<td>Evaporator</td>
<td>Evaporator size</td>
<td>25 mm thick and fits plan form of MCM top</td>
</tr>
<tr>
<td></td>
<td>Resistance between evaporator and hat</td>
<td>0.0015 C/W</td>
</tr>
<tr>
<td>Printed Circuit Board</td>
<td>Board in plane thermal conductivity-</td>
<td>20 W/mK</td>
</tr>
<tr>
<td></td>
<td>Board perm. thermal conductivity</td>
<td>0.5 W/mK</td>
</tr>
<tr>
<td></td>
<td>Board Size</td>
<td>56 cm x 45.7 cm x 6 mm</td>
</tr>
<tr>
<td>Insulation</td>
<td>Thermal conductivity</td>
<td>0.1 W/mK</td>
</tr>
</tbody>
</table>
Table 2. Results of the resistance network analysis.

<table>
<thead>
<tr>
<th>Option</th>
<th>( T_{\text{amb.}} ) °C</th>
<th>( T_{\text{evap.}} ) °C</th>
<th>( T_{\text{Chip}} ) °C</th>
<th>( T_1 ) °C</th>
<th>( T_2 ) °C</th>
<th>( T_3 ) °C</th>
<th>P W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>19.5</td>
<td>28.16</td>
<td>21.05</td>
<td>30.41</td>
<td>31.73</td>
<td>929.63</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>9</td>
<td>17.68</td>
<td>21.04</td>
<td>28.10</td>
<td>28.23</td>
<td>933.97</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>9</td>
<td>17.68</td>
<td>21.04</td>
<td>24.30</td>
<td>28.36</td>
<td>934.32</td>
</tr>
</tbody>
</table>

Table 3. Analytical and numerical solution results for option 3.

<table>
<thead>
<tr>
<th>Model</th>
<th>( T_{\text{evap.}} ) °C</th>
<th>( T_{\text{Chip}} ) °C</th>
<th>( T_1 ) °C</th>
<th>( T_2 ) °C</th>
<th>( T_3 ) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 3</td>
<td>9</td>
<td>17.68</td>
<td>21.04</td>
<td>24.07</td>
<td>28.36</td>
</tr>
<tr>
<td>Numerical</td>
<td>10.13</td>
<td>16.66</td>
<td>21.34</td>
<td>26.6</td>
<td>27.78*</td>
</tr>
</tbody>
</table>

* Average temperature around the module

6 COMPARISON AND DISCUSSION

Results of the analytical and numerical models are given in Table 3. Temperature \( T_1 \) represents the average temperature of the top insulation. A difference of 0.3 °C between the analytical model and the numerical solution is seen. However, the local temperature on the top insulation is different from the average. This difference cannot be predicted by the analytical model. In the analytical model, it is assumed that the thermal boundary layer starts at the ambient temperature on the upper corner of the top insulation vertical panel. This was not the case when the cold air from the board upper portion falls over the module. The air temperature at this point is about three degrees lower than the ambient temperature. In order to determine the local surface temperature, a numerical model or experimental results are needed.

The analytical model predicts the average bottom insulation temperature \( (T_2) \) within 2.53 °C. Also, the model predicts the board temperature at the outer edge of the module \( (T_3) \) within 0.58 °C. These differences might be quite reasonable for preliminary design evaluation purposes.

The main source of the differences is a lack of a simple model for the air side heat transfer coefficient on the board with non-uniform boundary conditions.

7 CONCLUSIONS

A model for heat spreading in orthotropic materials has been developed. In order to evaluate the developed model for MCMs’ thermal analysis, the heat transfer inside a refrigeration cooled multi-chip module of an IBM CMOS Server has been considered. This study proves that the analytical models are effective tools for thermal design process of the MCMs. The developed model enables us to predict temperature distribution at entire module with an acceptable accuracy. Using a simple computer routine for solving the resistance network, one can calculate the required insulation thickness, junction temperatures, and evaporator cooling capacity for different design options. The results of the calculation for the overall geometry and sizes plus evaporator cooling capacities can be used for a more detail study of the local temperature distribution in a numerical simulation or experimental study.

Development of an appropriate model for airside heat transfer coefficient on PCB will improve the developed model in a sense that it can provide better prediction for the PCB and module contact temperature.
ACKNOWLEDGEMENTS

The parameters in Table 1 were provided by Dr. Roger Schmidt from IBM as part of a design case study conducted in the course ENME 808 W at the University of Maryland during Spring 2001. We thank Dr. P. Sathyamurthy for making the IcePack code available at the University of Maryland.

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