Strategies for CFD Modeling

of Complex PCBs

Thermal design for modern electronics is increasingly difficult. The back of a napkin approach, along with simple analyses, was often sufficient. But today's assemblies pack higher powered components in an ever decreasing space, which greatly increases the coupling effect of neighboring components. It is no longer possible to look at each component individually and design a discrete solution. This move from component level analysis to board and chassis level analysis has rendered the analytical approach to no more than a first estimate, if useful at all.

The development of computational fluid dynamics in modern design allows for a higher level of upfront analysis; however, there is a steep learning curve associated with its accurate use. This article highlights work done on the set up of CFD simulations, best practices and potential issues.

CFD Model Setup

Prior to running a CFD simulation, it is important to set up the test model carefully to ensure accurate results and reduce computational time. When creating a model, it's advisable to use compact and detailed thermal models to represent components and heat sinks. The following is an explanation of each type of model by Shidore [1].

What is a Detailed Thermal Model (DTM)?

A DTM is a model that attempts to represent or reconstruct the physical geometry of a package to the extent feasible. Thus, a detailed model will always look physically similar to the actual package geometry. Constructing a DTM in a thermal analysis tool is made easier by integrating mechanical CAD data for the part. A properly constructed, detailed model is, by definition, boundary condition independent (BCI). The model will accurately predict the temperature at various points within the package (including junction, case and leads), regardless of the cooling environment in which it is placed.

DTMs are suitable for use in simulating designs, in which the number of packages is few. For example, typical package thermal θ_{ja} racterization problems such as calculat θ_{ja} to extract (junction-to-air thermal resistance) or (junction-to-moving air thermal resistance) fall under this category. However, DTMs are not feasible simulating sub-systems or system-level computations, which involve a large number of semiconductor packages. This is because the computational resources required for solving such large problems would be excessive if each package were to be represented by a DTM. These are precisely the applications where a CTM – compact thermal model – should be used.

What is a Compact Thermal Model (CTM)?

A CTM is a behavioral model that aims to accurately predict the temperature of a package at only a few critical points e.g., junction, case and leads; but does so using far less computational effort. A CTM is not constructed by trying to mimic the geometry and material properties of the actual component. Rather, it is an abstraction of the response of a component to the environment it is placed in.

Most CTM approaches use a thermal resistor network to construct the model, analogous to an electrical network that follows Ohm's law. The most popular types of CTMs in use today are two-resistor and DELPHI.

Two-Resistor CTMs

A simple and widely-used CTM is a two-resistor model (Figure 1). It consists of a thermal resistance from the junction to the board (junction-to-board resistance, or θ_{ja}) and one from junction to case (junction-to-case resistance, or θ_{jc}). Both of these parameters are defined by the JEDEC industry standards committee [1] as reference standards.

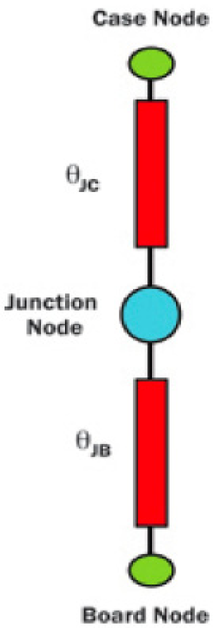

Figure 1. A Two-Resistor Compact Thermal Model [1].

The junction-to-case resistance (θ_{jc}) is normally derived from a "top cold plate test", in which the package is placed on a board with all sides insulated except the top surface. A cold plate, at a specified temperature, is pressed against the top surface. Hence, most of the power dissipated from the package leaves through its top (isothermal) surface. The one-dimensional equivalent of Fourier's law is then applied to derive θ_{jc}.

Thus,

$$\theta_{jc} = (T_j - T_{cld}) / P \qquad (1)$$

Where T_j is the junction temperature and T_{cld} is the temperature of the cold plate. The junction-to-board resistance (θ_{jb}) is derived by placing the package in a specially constructed harness known as the ring cold plate. The plate (Figure 2) fixture consists of a 4-layer PCB inserted between two cold plates. The cold plates are in the shape of a ring. Thus, heat travels from the package through some distance within the board and then out of the fixture through the coolant fluid in the cold plate.

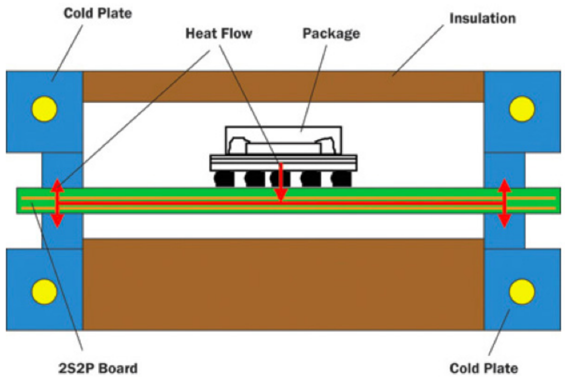

Figure 2. Fixture for Measuring θ_{ja} [1].

R_{jb} is calculated by using the one-dimensional version of Fourier's law:

$$\theta_{ja} = \frac{T_j - T_b}{P} \qquad (3)$$

The board temperature (T_b) is taken at a point on the board surface located in the middle of the longest side of the package, no more than 1 mm from the package edge for an area array package and on the center lead foot for a surface-mount leaded package.

A two-resistor model has the following advantages:

- Its structure is simple and intuitive.
- It can be created from existing test data.
- It results in a significant increase in accuracy for predicting junction temperature compared to traditional single-resistor metrics such as θ_{ja}.

Simulation Accuracy and Uncertainties

Despite careful modeling, the accuracy of a given CFD simulation can vary by a great degree. The amount of simplification and estimation, by both the software and the user, will directly influence the results. It is generally accepted to use CFD results as a basis for comparison and to validate all results with experimental testing.

Very thorough papers on the accuracy of CFD simulations were written by Lasance [2], [3]. These deal with the many uncertainties of a model. The author also expanded on the possible overall error, which reflects the need for correlation and calibration of the CFD model.

Lasance goes on to explain the correlation of CFD results to experimental models, and the potential for very poor agreement between the two [2].

Consider a situation in which substantial differences are found between the results of a CFD analysis and experimental results. Let us further assume that the experiment is well designed, so that the results are correct to within 5%, based on 20:1 odds. The question arises: How accurately are the real physics simulated by the numerical analysis and how accurately are the physical properties and input parameters known? Table 2 provides plausible uncertainty contributions to the calculation of junction temperatures.

Numerical	Experimental	Input Data	'Comparison Mismatch'	
Discretization method	Sensor calibration	Thermal conductivity	*Experimental*	*Numerical*
False diffusion	Equipment	Board parameters	pn-junction	Max. junction-T
Modelling resolution	Data acquisition	Emissivity	Point sensor	Cell average
Mesh independence	Sensor disturbance	Interface resistance	Integrating sensor	Velocity vector
Temperature dependence	Changing ambient	Component data		
Radiation approximation		Power dissipation		
Complex geometries		Air resistance coefficients		
Geometry representation		Roughness		
Complex physics				
Turbulence models				
Transient effects				
Boundary conditions				

Table 1. Uncertainties of Numerical and Experimental Results [2].

Numerical Errors	Error (%)	Input Data Errors (see text)	Resulting Error (%)	Mismatch Errors	Error (%)
Algorithms	5	Thermal conductivity	10	Junction	Any
Discretization	5	Emissivity	5	Averaging	Any
Radiation	5	Interfaces	10		
Complexity	10	Component data	10		
		Dissipation	Up to 10		

Table 2. Estimated Uncertainty in Junction Temperature [2].

Assume a brilliant designer with lots of time succeeded in reducing all errors to 5%. Taking the root mean square of the error percentages, the final error is of the order of 20%, notwithstanding the fact that the numerical and experimental analyses do meet current standards. The reader may wonder why these problems never show up in reports and literature. The reason why impressive results are often claimed can be attributed simply to the fact that many parameters are available that can be used to match the results. In this way, it is relatively simple to reduce the errors to something between 5 and 10%. It should be stressed that nothing is wrong with this practice; the problem is that it is often argued that the numerical code has been validated, while it is really calibration that we are talking about. Although it may seem only an academic distinction, it is not. Calibration does not guarantee extrapolation to other situations, while validation does.

How to Improve?

We may expect that some errors will decrease to more acceptable levels on the numerical side. The errors related to the treatment of complex fluid phenomena will not be reduced to the same extent unless Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) techniques become feasible for 3D complex systems. While it is true that some improvement could be gained by implementing more sophisticated turbulence models [2] it is by no means a panacea for the problems mentioned. Suppose we want to model spray cooling. It makes a lot more sense to design appropriate experiments to estimate the local heat transfer instead of relying on very complex 3D highly turbulent two-phase CFD simulations.

One way to enhance the predictability of CFD analyses is to use a pragmatic approach by employing correction factors. A recommended way to measure correction factors is by developing ‘ideal’ experimental benchmarks for complex geometries where all boundary conditions and material properties are under control and are well known to within a few percent [1].

Conclusions

The continually shrinking time-to-market for electronic products will require an ever- increasing reliance on computational simulations. However, a number of issues still impede a greater reliance on predictive modeling capabilities. In particular:

- Computational resources for handling large, realistic problems,
- Databases on thermo physical properties of electronic packaging materials
- Accurate in-situ determination of physical properties,
- Assessment of interfacial thermal resistances,
- Wide availability of compact models supplied by vendors, and
- Accurate benchmarks to assess and correct the influence of complex geometries.

Here is the most important conclusion to emerge from this article: A numerical analysis of an electronic system may or may not be correct, and no one can tell. Suppose the calculated and measured junction temperatures differ by 20%, then it is still possible that both analyses are correct to within 5% or better, simply because sufficiently known input data are lacking. Another way to put it: An accurate match (10%) is not possible without some kind of fitting. Despite the conclusions, CFD tools are vital in design environments! However, do not expect or claim high accuracy in a direct comparison with experiments..

References:

1. Shidore,S., Compact Thermal Modeling in Electronics Design, Electronics Cooling Magazine, May 2007.

2. Lasance,C.,The Conceivable Accuracy of Experimental and Numerical Thermal Analyses of Electronic Systems, IEEE CPT 25, 2002.

3. Lasance,C.,Problems with Thermal Interface Material Measurements: Suggestions for Improvement, Electronics Cooling Magazine, November 2003.