Transient Coupled Thermal / Electrical Analysis of a Printed Wiring Board

Ben Zandi –TES International: (248) 362-2090 bzandi@tesint.com
Jeffrey Lewis –TES International
Hamish Lewis –TES International

Abstract
The impact of coupling of the thermal and electrical solutions for a given circuit board is demonstrated to be important for the accurate prediction of temperature profiles. The significance of this has been demonstrated in numerous real life cases and the coupled solution has been shown to be a much better representation of the actual observed numbers in every instance. This paper presents a numerical investigation of transient and steady-state heat transfer in a multilayered printed wiring board (PWB) where heat is dissipated as a result of flow of electrical current in various areas in the board. The numerical model consists of a six-layer PWB with eight capacitors on each side of the board. Electrical current enters the board through "load" terminal blocks and leaves the board through "return" terminal blocks. The load layers and the return layers are electrically and thermally connected using "vias". The transient solution is performed for two minutes in order to examine a "worst case" condition for the given configuration.

In these types of applications, the heat dissipation distribution is not known prior to the solution and must be evaluated by simultaneously solving the electrical field. This is accomplished through a "coupled electrical/thermal solution" scheme, where the voltage field is solved throughout the region knowing electrical loads and boundary conditions (in addition to thermal and flow fields) during each iteration. The most recent temperature field is used to update the electrical resistivity of the conductors in the model. The power dissipation is then calculated for all elements. For an element in a Cartesian coordinate system the power dissipation as a result of Joulian heating is given by:

$$P_{Element} = \frac{(\Delta\phi_x)^2}{R_x} + \frac{(\Delta\phi_y)^2}{R_y} + \frac{(\Delta\phi_z)^2}{R_z}$$

where ϕ is Voltage and Rx, R_y and R_z are resistance x, y and z directions.

Introduction
The cooling of electronic components is one of the most important tasks in the design and packaging of electronic equipment. In some equipment, the thermal (cooling) design is as important as the electronic design. Insufficient thermal control can lead to poor reliability, short life and failure of the electronic components.

This study shows how numerical simulation can be used to predict transient thermal performance of a circuit board subjected to a "worst case" heating scenario. The main difficulty in this analysis comes from the fact that the majority of the heat is dissipated as a result of the flow of electrical current in various conductors. In order to predict temperatures accurately, the important mechanisms for heat generation and heat transfer must be adequately considered. The issue that complicates matters is that the amount of heat generated by the electric current flowing through the board is itself dependent on temperature, thus requiring an approach that considers the coupling between the electrical and thermal aspects of the model. The current density and resulting power dissipation are calculated with electrical numerical analysis. The coupling with the thermal problem is achieved by specifying the resistivity of the conductor as a function of the calculated temperatures.

We have developed a computational procedure that can be used to address the main difficulties encountered in practical electronics cooling applications. In the open literature, no references could be found to centrally address the key issues involved in the coupled nature of thermal, CFD and electrical analysis. There is, however, a paper by Doerstling [1] that addresses the main difficulties and outlines a procedure that utilizes four commercially available software packages. He presents an approach combining electrical and thermal analyses to predict the thermal performance of electrical centers and junction blocks. A method for creating a system level steady state model of a bussed electrical center (BEC) is demonstrated. Several BEC designs are modeled using a largely automated process.

Problem Statement
Figure 1 shows a sketch of the system. The region of interest consists of a sealed aluminum enclosure (5.4 in x 3.9 in x 1.4 in) that houses a multilayer printed wiring board (PWB) horizontally oriented in an ambient temperature of 70 °C with no forced flow. The flow of electrical current through various layers in the board is accompanied with generation of heat in the board. Consequently, the board temperature rises, and unless the heat is transferred to the surroundings efficiently, this temperature will reach critical levels leading to failure of the electronic device. In this study, the resulting transient conduction and natural convection flows are numerically investigated and the main focus is placed on the effect of the inherent coupling that exists between the electrical and thermal fields.

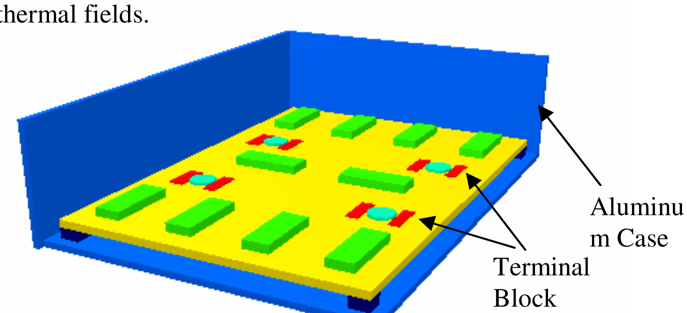

Figure 1: Enclosure and Board Geometry

Board Geometrical Details:
The board is 5 inches long, 3.5 inches wide and 0.09 inches thick and contains 6 copper layers, 4 terminal blocks and 10 capacitors. The layers are 0.005 inches thick and they are geometrically identical. There are 3 load layers providing the electrical current to the capacitors and three return layers to pass the current back to *return* terminal blocks. All load layers and return layers are electrically connected using vias.

Electrical current enters the board through the "load terminal blocks". From there it flows through vias to all *load* layers and to the capacitors. The return current flows back to the *return* terminal blocks, passing through *return* layers and vias. The vias were assumed to have a conducting area of 0.00125 in^2 and a p

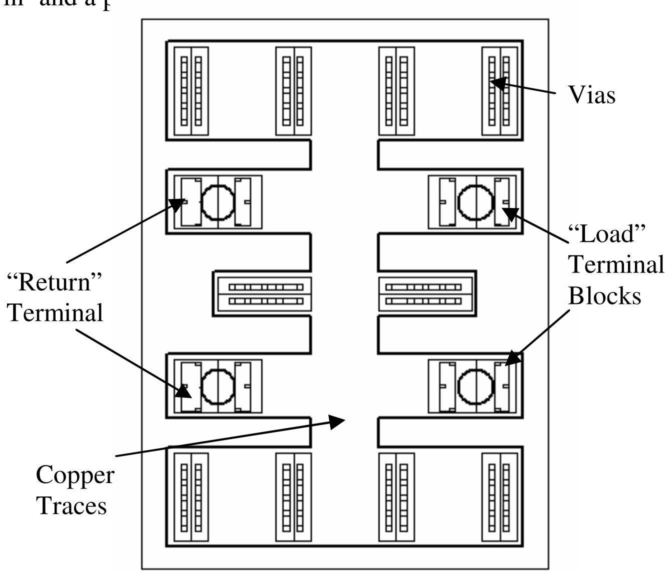

Figure 2: Board Layout and Copper Traces

Material Properties:
The following table provides a listing for all materials used in the model along with their thermo-physical properties:

	Thermal Conductivity (W/m.K)	Specific Heat J/(kg.K)	Density kg/m^3
Epoxy Fiberglass	0.29	1256	1135
Copper	401	385	8933
Aluminum	177	875	2770
Plastic	0.3	1150	1217

The electrical resistivity for copper is calculated from:

$$\rho_e = \rho_0 \left[1 + \alpha\left(T - T_0\right)\right]$$

T_0 ≡ Reference Temperature = 20 °C

ρ_0 ≡ Resistivity at T_0 = 0.0175e-06 $\Omega.m$

α ≡ Resistance Temperature Coefficients = 0.0039 $°C^{-1}$

Theory and Governing Equations
The prediction of heat transfer and flow requires understanding the values of the relevant variables (temperature, velocity, pressure, etc.) throughout the domain of interest. In order to predict temperatures within a PWB accurately, the important mechanisms for heat generation and heat transfer must be adequately considered. The issue that complicates matters is that the amount of heat generated by the electric currents flowing through vias and trances is itself dependent on temperature, thus requiring an approach that considers the coupling between the electrical and thermal aspects of the model.

For a system consisting of a printing wiring board inside a sealed enclosure, the governing conservation equations for mass, momentum and energy are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

(1)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + F_x$$

(2)

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + F_y$$

(3)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + F_z$$

(4)

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q'''$$

(5)

Where:

- x, y, z ≡ Cartesian Spatial Coordinates
- t ≡ Time
- u, v, w ≡ Velocity Components in x, y and z
- T ≡ Temperature
- ρ ≡ Density
- μ ≡ Dynamic Viscosity (1^{st} Coefficient)
- k ≡ Thermal Conductivity
- q‴ = Volumetric Heat Generation
- C_p ≡ Specific Heat at Constant Pressure

Note that the volumetric heat generation term, q‴, represents total heat dissipation in element. This includes the Joulian heat dissipation (as a result of current in conductors) which is not known prior to the solution and must be evaluated by simultaneously solving the electrical field. This is accomplished through a "coupled electrical/thermal solution" scheme, where the voltage field is solved throughout the region knowing electrical loads and boundary conditions (in addition to thermal and flow fields) during each iteration. The most recent temperature field is used to update the electrical resistivity of the conductors in the model. The power dissipation is then calculated for all elements. This procedure is described below. The solution procedure is described in more detail in the following sections.

The voltage field, ϕ, satisfies the following partial conservation equation:

$$\frac{\partial}{\partial x}\left(\mathrm{K}\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mathrm{K}\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mathrm{K}\frac{\partial \phi}{\partial z}\right)=0$$

(6)

The electrical conductivity is defined as $\mathrm{K}=\frac{1}{\rho_e}$, where ρ_e is the electrical resistivity of the conductor and is related to temperature by: $\rho_e=\rho_0\left[1+\alpha\left(T-T_0\right)+\beta\left(T-T_0\right)^2\right]$

Where:

ρ_0 ≡ Resistivity at Reference Temperature (T_0)

α, β ≡ Resistance Temperature Coefficients

The current density, $\vec{J}$, is related to the electrical field, $\vec{E}$, by ohm's law, which for an isotropic conductivity medium with electrical conductivity, K, is given by:

$$\vec{J}\left(\vec{x}\right)=\mathrm{K}\left(\vec{x}\right).\vec{E}\left(\vec{x}\right)$$

(7)

The electrical field is expressed as the gradient of the voltage field:

$$\vec{E}\left(\vec{x}\right)=-\nabla\phi\left(\vec{x}\right)$$

(8)

The total rate of work done in an element with volume V is:

$$P=\int_V \vec{J}.\vec{E}dV=\int_V \mathrm{K}\nabla\phi.\nabla\phi dV$$

(9)

Therefore, the power dissipation in one element is given by:

$$P_{Element}=\mathrm{K}V_{Element}\nabla\phi.\nabla\phi=\frac{V_{Element}}{\rho_e}\nabla\phi.\nabla\phi$$

(10)

For a Cartesian element this reduces to

$$P_{Element}=\frac{\left(\Delta\phi_x\right)^2}{R_x}+\frac{\left(\Delta\phi_y\right)^2}{R_y}+\frac{\left(\Delta\phi_z\right)^2}{R_z}$$

(11)

R_x, R_y and R_z are resistance x, y and z directions.

A complete and thorough discussion of the above is presented in the book by J. D. Jackson [3].

Computational Details:

The important operations for the solution of transient coupled Thermal – Electrical – CFD problem are described below, in the order of their execution:

1. **Initialization:**

All relevant parameters that define the problem are read by the program and loaded into the computer memory. This includes geometrical parameters, thermal CFD and electrical loads and boundary conditions, thermal and electrical properties for all solids in the model.

2. **Solve for the initial voltage field:**

Using the values for the electrical resistivity (evaluated at the initial temperature) the voltage differential equation (Eq. 6) is solved in all electrically conducting regions in the model subject to current and voltage boundary conditions.

3. **Obtain the initial Joulian heat dissipation:**

Knowing the values of the voltage at all electrically conductive elements, the Joulian heat dissipation is calculated from Eq. 11 and added to the element "source term".

4. **Solve for temperature and flow fields for the initial time level:**

Next, the differential equations for energy and flow are solved throughout the domain of interest to yield values for the temperature, velocity components and pressure for all elements in the model. This requires knowledge of:

- The initial temperature and flow distribution.
- Thermo-physical properties for all solids and fluid regions.
- Thermal and flow boundary conditions.
- The values of heat sources at all conductors obtained from the previous step.

The SIMPLER algorithm is used to couple the continuity and momentum equations. The reader should refer to reference [4] for details of this algorithm.

5. **Update Material Properties:**

All material properties (including the electrical resistivity) are updated to correspond to the current temperature field.

6. **Solve the electrical field:**

Using the updated values for the electrical resistivity, solve for the voltage field. Update heat sources to account for changes in the Joulian heat dissipation resulting from the changed electrical field.

7. **Solve for temperature and flow:**

Using the updated material properties and the current temperature and flow fields, increment the time and solve the governing differential equations to obtain temperature and flow for the current time iteration.

8. **Iterate:**

Return to step 5 and repeat the entire procedure until the end time is reached.

Results

The goal of this study was to demonstrate the differences in the predicted temperature field for the board after two minutes of high current flow with and without coupling of electrical effects. However, simulations were performed for both steady-state and transient conditions. Figure 3 and Figure 4 provide the steady-state velocity and temperature fringe plots. The maximum board temperature was 181 °C and the maximum velocity was 14.3 cm/sec.

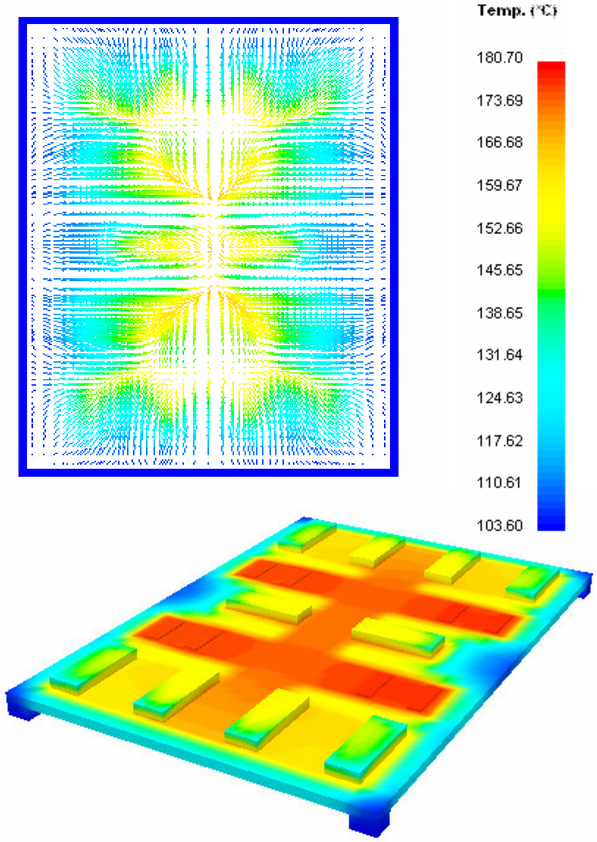

Figure 3: Velocity and Temperature Fringe Plot

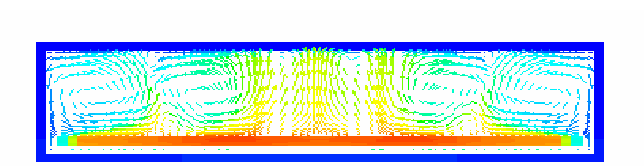

Figure 4: Velocity Fringe Plot (xz plane)

Transient Results

The results below demonstrate the difference between an analysis done with the thermal and electrical solutions coupled and with the electrical solution done first and the thermal analysis done separately as would be done with most software packages.

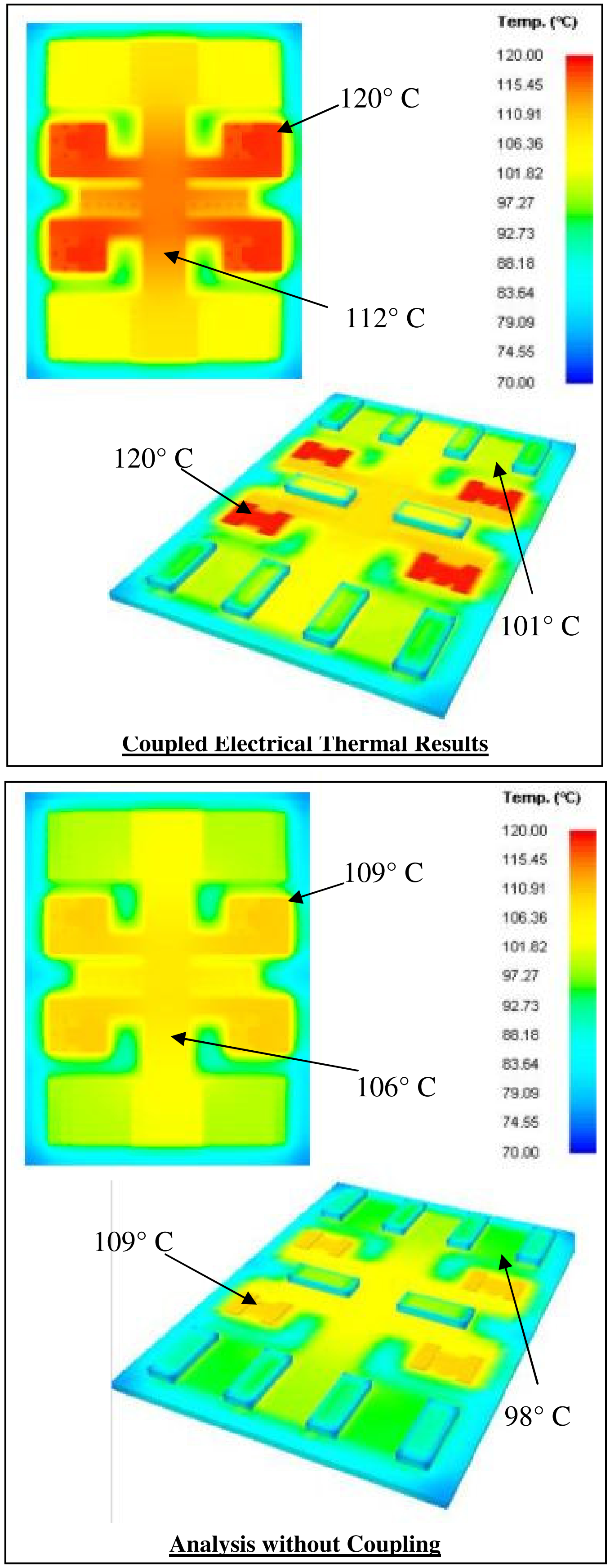

Figure 5 Temperature Distribution After 2 Minutes

The more accurate coupled analysis predicts a temperature rise 8 degrees higher than would be obtained with a standard software package after only 2 minutes. Since the maximum allowable temperature in this case is 115 degrees, the coupled correctly predicts failure whereas the standard non-coupled technique predicts that there should be no problem

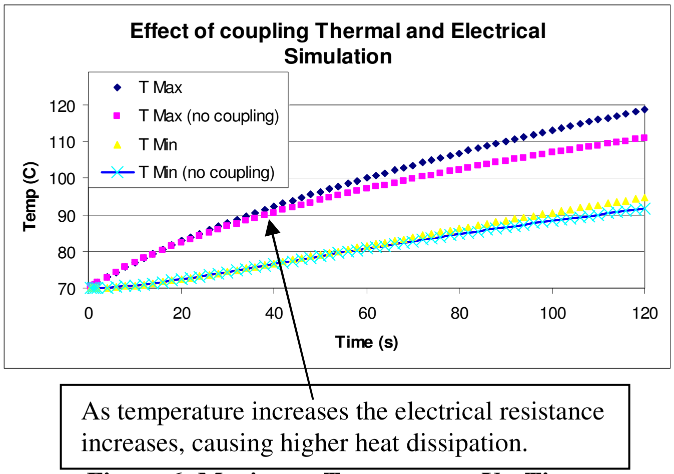

Figure 6: Maximum Temperature Vs. Time

Description of Software

All modeling and numerical simulations for this study were performed using ElectroFlo® (EFlo), a commercially available software package developed by Zandi that has been used for over 10 years, although many features have been added more recently. EFlo is a finite volume based package [4] which incorporates the most important features for electronics cooling analysis. One of the key features which is relevant to this particular study is the use of coupled thermal/electrical algorithms in the solution. Thus, the thermal problem is solved simultaneously with the electrical field. This is important because the resistance of an electrical circuit varies with temperature which then impacts the voltage and current fields in the circuit and the heat dissipated is a function of the current and resistance in each part of the circuit. The use of coupled thermal/electrical allows for local solution which results in a much more accurate point reading of temperature than would otherwise be possible. The solution method involves many iterations and the electrical properties and thermal properties are both re-calculated during each iteration. This coupling becomes of greater value with the increasing demands on the electronics used in many areas. The increased accuracy and solution speed afforded become invaluable.

The package has computational fluid dynamics capability, although it can be run either with or without this feature turned on. A patented radiation solver is also incorporated.[5] In many cases radiation can be a more significant contributor to heat transfer than natural convection. The blocking technique used allows a much more efficient solution than would other wise be possible.

All simulations were run on a standard windows based PC.

Conclusions

The effect of coupling the thermal and electrical solutions was demonstrated. Failure to recognize the effect of the thermal gradients on the electrical properties of the system would have resulted in an inaccurate model prediction. In the example used the model would have predicted a failure with the coupled whereas without the coupled feature no flag would have been raised. In many areas electronic circuits have to run close to their acceptable limits and a difference of a few degrees in the temperature rise is very significant.

The ability to more closely simulate reality can result in not only better reliability of the circuits, but also may allow a substantial cost savings as passive cooling solutions may be possible in place of the more expensive active fans etc. Avoiding active cooling solutions in itself may result in greater reliability as the number of moving parts is reduced. Noise is another factor which could be relevant as fans tend to be the noisiest part of electronic systems.

References

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5. Zandi, B., US 5,937,369