Coupled Thermal / Electrical Analysis of High Powered Electrical Systems

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Abstract

This paper describes an approach based on coupled electrical, thermal and CFD analysis to predict the thermal performance of Bussed electrical centers and junction blocks. Typically from 200 to 400 amps flow trough various circuitries, which lead to a significant amount of Joule heat dissipation that is responsible for the majority of heat loss in the system. The Joule heat dissipation distribution is not known prior to the solution and must be evaluated by simultaneously solving the electrical field. This can be accomplished through a "coupled electrical, thermal solution" scheme, where the voltage field is solved throughout the region using the 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 and updated for all conductor elements.

In this paper, a thermal/electrical/CFD model of a typical Bussed Electrical Center (BEC) consisting of several relays, diodes and switches is discussed. The procedure for coupling the electrical and thermal effects is presented using 3D views of various circuitries. A discussion relating to the application of electrical boundary conditions (voltage and current BC's) is presented, followed by a detailed discussion of flow, thermal and voltage fields.

Nomenclature

C_p	Specific Heat at Constant Pressure
$\vec{E}$	Electrical Field
i	Electrical Current
$\vec{J}$	Current Density
k	Thermal Conductivity
$P_{Element}$	Power Dissipation in One Element
q'''	Volumetric Heat Generation
R(T)	Temperature Dependent Resistance Coefficient
R_x	Resistance in x Direction
R_y	Resistance in y Direction
R_z	Resistance in z Direction
t	Time
T_0	Reference Temperature = 20 °C
T	Temperature
u, v, w	Velocity Components in x, y and z directions
V	Volume
x, y, z	Spatial Coordinates in a Rectangular Cartesian Coordinate System
α	Resistance Temperature Coefficients= 0.0039 °C^{-1}
β	Resistance Temperature Coefficients
μ	Dynamic Viscosity (1st Coefficient of Viscosity)
σ	Electrical Conductivity
ρ	Density
ρ_0	Resistivity at T_0 = 0.0175e-06 $\Omega.m$
ρ_e	Electrical Resistivity

Introduction

The cooling of electronic components is one of the most important tasks in the design and packaging of electronic equipment as insufficient thermal control can lead to poor reliability, short life and failure of the electronic components. According to a study conducted by Philips Corporation, every ten degree Celsius increase in temperature causes a fifty percent decrease in the operating life of many integrated circuits [1].

With the increasing design complexity and reliability requirements, today's electronic design engineers rely significantly on software packages (often based on methods of Computational Fluid Dynamics, or CFD) for the prediction of the operational temperature. In the early to intermediate product design phase, numerical analysis is used to select a cooling strategy and refine a thermal design by parametric analysis. In the final design phase, detailed analysis of product's thermal performance is carried out for performance and reliability predictions. However, it is recognized that, for a large class of electronics applications, progress in reliability prediction is currently hampered by the lack of accurate prediction methods. This is especially true for problems in which there is significant heat generation due to the flow of electrical currents in traces and conductors. References [2 – 4] are examples studies involving numerical natural convection in enclosures with heated components.

Today's electronic design engineers are faced with challenging thermal management problems resulting from high current densities in increasingly small boxes packed with temperature-sensitive electronic components. Proper evaluation and treatment of heat dissipation as a result of the flow of electrical current in traces and conductors is of utmost importance in thermal management of many classes of electronics designs. Unfortunately, most software programs are not capable of centrally addressing the thermal issues relating to the electrical current flow in traces and conductors.

Flow of electrical current in traces and conductors is always accompanied by heat generation. This effect is called Joule heating (or Joule heat dissipation.) in honor of its discoverer, James Joule. Joule heating plays a prominent role in the thermal design of many classes of electronic equipment. These problems cannot be solved using traditional heat transfer methods - they require the coupled solution of the voltage field that is needed to obtain the local rate of Joule heat dissipation

through all conductors in the field. The need for the coupling of electrical and thermal aspects of the model is due to the fact that the amount of heat generated by the electric current flowing through the device is itself dependent on temperature [5 - 7]. The significance of temperature-dependent effects is well documented and will be addressed in this study.

Problem Statement
A Bussed Electrical Center (BEC) is a power and signal distribution device where electrical switching and circuit protection components are combined into a single system. These designs contain components such as relays, fuses and circuit breakers, which are connected through an array of stamped metal bussing, traces and routed wires. The housing is made of a variety of molded plastic parts. It is estimated that Joule heating is responsible for close to half of the total heat dissipated in these devices. The heat dissipation distribution is not known prior to the solution and must be evaluated by simultaneously solving the electrical field. This can be 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.

Figure 1 illustrates the modeled BEC with multiple boards and components (i.e., relays, fuses, diodes). Figure 1 shows the electrical circuitry for this system. Typically, 100 to 200 amps flow trough various circuitries, which leads to significant amount of Joule heat dissipation.

Details of the Model
The region of interest consists of a sealed plastic enclosure (22.4 cm x 13.5 cm x 6.5 cm; 2 mm thick) that houses relays, fuses and circuit breakers. In the current model, the BEC consists of two layers. The devices are placed on the upper layer. The lower layer creates the connection between the devices through an assembly of stamped metal and traces; bare copper conductors that are placed into grooves on plastic plates.
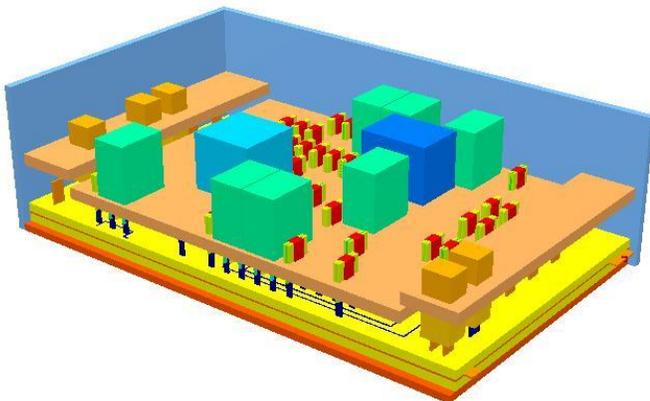

Figure 1: Typical Multi-board Junction Box

Internal Heat Transfer: The internal heat transfer will be due to conduction, natural convection and radiation. To accurately account for conduction, one must take extreme care in the modeling of the relevant geometry, conduction paths and thermal conductivities of materials. The convective heat transfer is accounted for by solving the full fluid dynamics problem using CFD. Since the flow within the enclosure is strictly by natural convection, thermal radiation can play a significant role and must be included in the analysis.
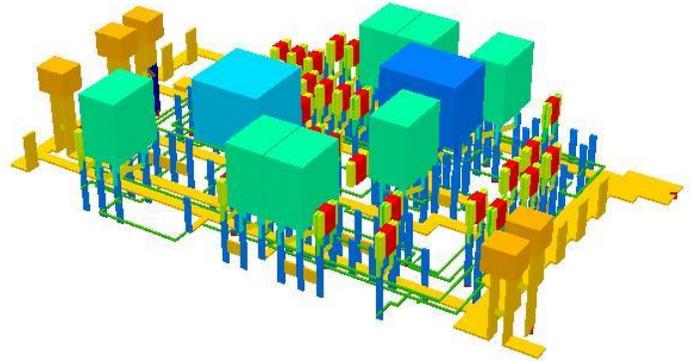

Figure 2: Network of Connectors and Traces

Heat Generation: The heat generation in the system is due to Joule heating with bulk and contact resistances. For the modeled devices, this heating is calculated using $i^2*R(T)$, combining bulk and contact effects. The lumped approach is not applicable for modeling of heat generation in electrical conductors as a result of the flow of electrical current; the current density and the resulting heat dissipation is obtained by the coupled numerical solution. The details of this procedure are described in the upcoming sections.

Thermal Boundary Conditions: It is assumed that the BEC is located in quiescent ambient air at 105 °C (worst case, automotive underhood conditions). Also, since the computational domain is terminated at the edges of the enclosure, convection heat transfer boundary conditions are used to account for the transfer of the heat from the enclosure to the ambient. The standard correlations for natural convective heat transfer from vertical and horizontal surfaces are used in this model.

Material Properties: Table 1 provides a listing for all materials used in the model along with their thermo-physical properties. The electrical resistivity for copper is calculated from:

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

Material	Conductivity (W/m.K)	Resistivity (Ω.m)	α (°C⁻¹)
Copper	399.1	0.0175	0.0039
Plastic (Walls)	0.18	N/A	N/A
Component Bodies	0.51	N/A	N/A
Board	0.95	N/A	N/A

Table 1: Material Properties

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 throughout the system, 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 traces 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 printed wiring board inside a sealed enclosure, the governing conservation equations for mass, momentum and energy are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

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

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + F_y$$
$$(3)$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + F_z$$
$$(4)$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q'''$$
$$(5)$$

Note that the volumetric heat generation term, q''', represents total heat dissipation in element. This includes the Joule 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:

$$\frac{\partial}{\partial x}\left(K\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial \phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial \phi}{\partial z}\right) = 0 \qquad (6)$$

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

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, σ, is given by:

$$\vec{J}(\vec{x}) = \sigma(\vec{x}).\vec{E}(\vec{x}) \qquad (7)$$

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

$$\vec{E}(\vec{x}) = -\nabla\phi(\vec{x}) \qquad (8)$$

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

$$P = \int_V \vec{J}.\vec{E}dV = \int_V \sigma\nabla\phi.\nabla\phi dV \qquad (9)$$

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

$$P_{Element} = \sigma V_{Element}\nabla\phi.\nabla\phi = \frac{V_{Element}}{\rho_e}\nabla\phi.\nabla\phi \qquad (10)$$

For a Cartesian element this reduces to

$$P_{Element} = \frac{(\Delta\phi_x)^2}{R_x} + \frac{(\Delta\phi_y)^2}{R_y} + \frac{(\Delta\phi_z)^2}{R_z} \qquad (11)$$

A complete and thorough discussion of the above is presented in the book by J. D. Jackson [2].

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 Joule heat dissipation distribution:
Knowing the values of the voltage at all electrically conductive elements, the Joule 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 [3] 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 Joule 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

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 [4]. 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.

Results
The numerical analysis predicts a maximum velocity of 7.62 cm/sec and a maximum temperature of 175.2 °C. Figure 3 shows the three-dimensional temperature fringe plots.

Figure 4 shows the temperature distribution in the electrical conductors and traces. The temperature field on a plane passing though the board and the main circuit is depicted in Figure 5. Figure 6 illustrates the temperature and velocity distribution in the vicinity of a relay.
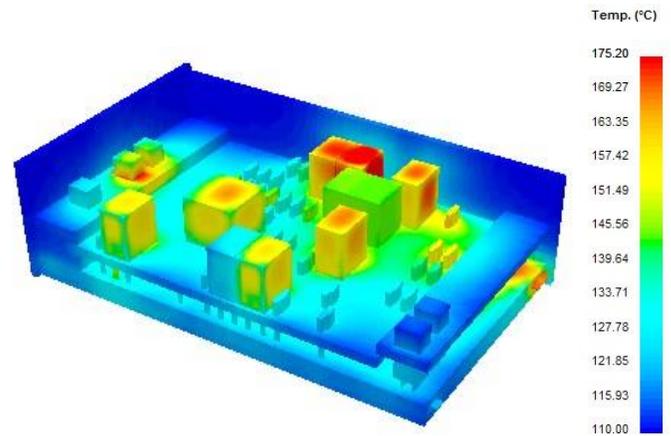

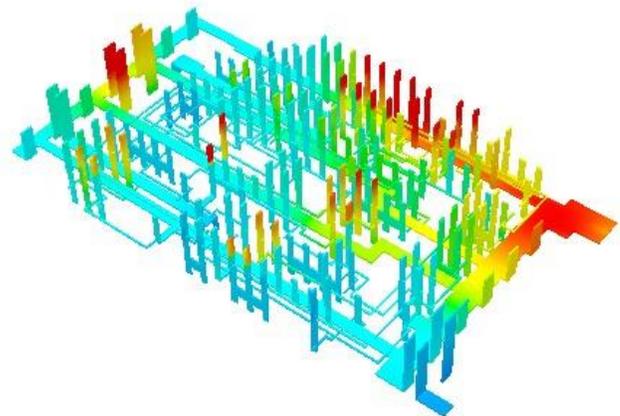**Figure 3: Temperature Distribution for BEC interior**

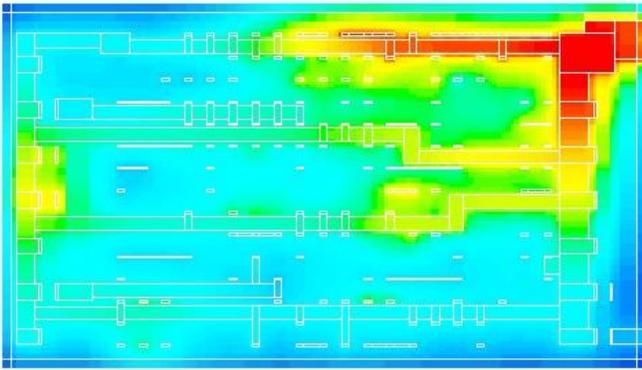**Figure 4: Temperature Distribution in Electrical Conductors**

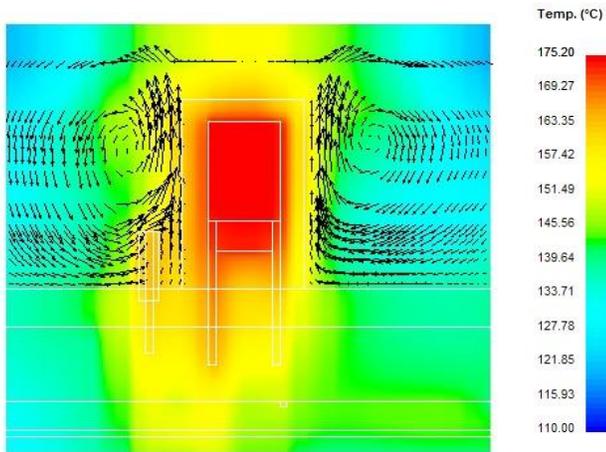**Figure 5: Circuit Board Temperature Distribution**

Figure 6: Temperature and Velocity around a Relay

Conclusions

This study points to a large class of electronics applications that require the coupled solution of heat transfer, flow and voltage fields. Without this coupling, the model would give misleading results. The procedure was demonstrated through the solution of a bussed electrical center. In these systems, a significant portion of the heat is due to the flow of electrical current in various circuitries. The only way to properly account for this heat dissipation is by solving the electrical field to obtain the current density distribution in all conductors.

The ability to more closely simulate reality results in not only better reliability of the circuits, but also may allow a substantial cost savings.

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