Multi System Multi physics approach for PCB and Enclosure Modeling

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Abstract

Despite the dramatic increases in the performance of desktop and even laptop computers in recent years, thermal analyses of systems containing multiple boards can take far too long. This may result in compromises to the modeling integrity that reduces the accuracy of the final models.

This paper presents a multi-system modeling approach that allows the user to run models of, for instance, a PCB board and the box that it is in as two separate models, but running them in parallel with boundary conditions being exchanged between them at every iteration. The models can be running on different machines, which could in theory be in different facilities or at least in different rooms.

The paper also addresses Joulean heating due to electrical current flow in the traces of the PCB. The board, which is heated electrically, is in an electronic enclosure and heat is dissipated from the board via natural convection to the enclosure and then by convection and radiation from the enclosure to the outside. The multi-system approach allows dramatically shorter run times and the analysts do not have to simplify the traces on the PCB and deal with convergence issues in this multi physics environment. The approach is illustrated using two examples.

The example involves the modeling of the trace/copper etching information of various board layers. Typically these layers of traces have to be manually created and connected or read in from a Gerber file. In this paper a model of a trace heated board in an electronic box is solved using the multi system approach. Traces in this example are created manually.

In this example the geometry of a board with trace layers is read in from a Gerber file and is run in conjunction with the system model that takes into account the fluid flow field calculated using CFD techniques and includes radiation. This type of detailed board model in conjunction with a CFD model of the enclosure would ordinarily be extremely large taking a long time to run and may run into convergence problems. The multi system approach dramatically improves both the run time and the probability of a successful convergence.

This paper describes an approach based on coupled electrical, thermal and CFD analysis to predict the thermal performance of electronic enclosures. Typically current flows through 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.

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. 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.

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 [3-5]. Modeling of the traces in a board can be achieved by creating the traces/ copper etching information manually, a very tedious and laborious task or reading it into the software through a Gerber file format written out by most ECAD systems. As the trace information gets voluminous, to capture all the details of the Joulean heating in the traces the board model gets more complex in its scope and size. The mesh density in the board may have to increase to capture this detail. When such a board model is stationed in the enclosure box to calculate the flow field in its surrounding the size and the number of elements in the CFD model goes up proportionately.

Problem Statement

The problem consists of an electronics enclosure with a PCB board. The board has a trace layer that carries a specified amount of current. The current flowing through the traces generates heat. 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.

Details of the Model:

The region of interest consists of a sealed enclosure (10 cm x 2.5 cm x 2.5 cm; 2 mm thick) that houses a typical PCB with trace layers. In the current model, the board consists of one layer. The copper traces in the board are read in from a Gerber (.gdo). There are three points where the current comes in to the traces and 3 points where it exits the circuit. Figures 1 and 3 show the model, and the Cartesian structured mesh. The mesh has 163350 elements. It can be observed that the mesh density is directly related to the complexity of the trace layers in the board model.

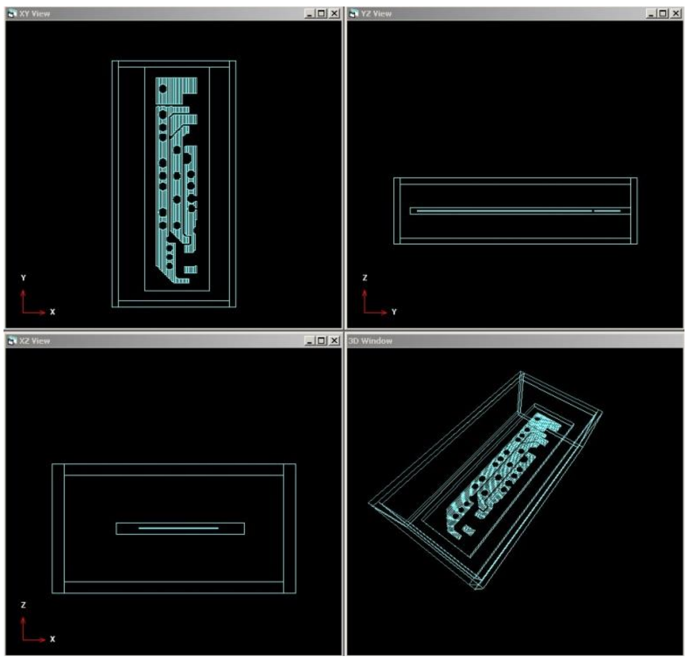

Figure 1: Typical electronic enclosure

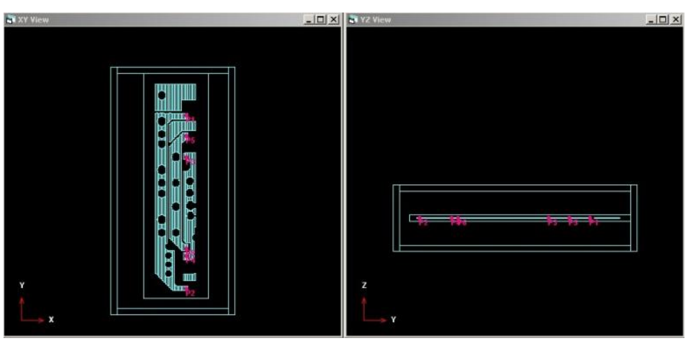

Figure 2: Current Inputs / Point Source Boundary conditions.

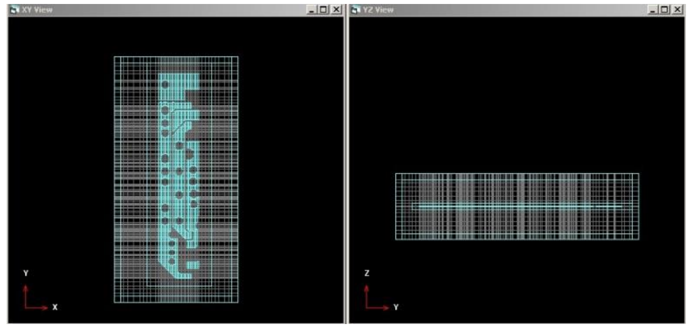

Figure 3: A structured Mesh for the Board/Enclosure Model

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.

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 enclosure is located in quiescent ambient air at 25 °C. Also, since the computational domain is terminated at the edges of the enclosure, convection heat transfer boundary conditions with h = 3 W/m2K are used to account for the transfer of the heat from the enclosure to the ambient.

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:

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

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

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

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

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

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:

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

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:

$$\rho_e=\rho_0\left[1+\alpha\left(T-T_0\right)+\beta\left(T-T_0\right)^2\right]$$

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:

$$\vec{J}\left(\vec{x}\right)=\sigma\left(\vec{x}\right).\vec{E}\left(\vec{x}\right) \quad (7)$$

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

$$\vec{E}\left(\vec{x}\right)=-\nabla\phi\left(\vec{x}\right) \quad (8)$$

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

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

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

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

For a Cartesian element this reduces to

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

A complete and thorough discussion of the above is presented in the book by J. D. Jackson [5].

Computational Details:

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

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.

1. 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.

2. 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".

3. 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 [7] for details of this algorithm.

4. Update Material Properties:
All material properties (including the electrical resistivity) are updated to correspond to the current temperature field.

5. 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.

6. 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.

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

Multi System Modeling:

The procedure outlined above is for a single system modeling. As mentioned earlier, many times the complexity of traces in the board model and the mesh needed to resolve the complexity and Joulean heating in the board propagates throughout the model and into the CFD region of the model and can increase the size of the CFD model as well. This can be very taxing on the computer resources and can result in high mesh densities in regions of the model not requiring the level of detail.

To address these issues we have adopted a multi system approach where the board and the enclosure it resides in can be treated as separate systems, each running independently with their own meshes and communicating with each other at the system boundaries. The models can be running on the same machine on different processors or can be running on different machines on a network. The speed of solution depends on the speed of the slowest system in the model. The two models can have their individual meshes suited for their own environment.

Description of Software

All modeling and numerical simulations for this study were performed using ElectroFlo® (EFlo), a commercially available software package developed by TES International. Eflo is a finite volume based package [7] which incorporates the most important features for electronics cooling analysis. One of the key features which are relevant to this particular study is the use of coupled thermal/electrical algorithms in the solution and the multi-system analysis. 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 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 [8]. 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.

The multi system approach gives the software flexibility in running different systems simultaneously on a network. This can speed up the solution as the complexities of board design do not propagate into the CFD domain and vice versa. This approach can be extended to run multiple systems that can be electronic boxes sitting in a complex enclosure that can be tied in through third party codes. For example all the electronic boxes can be analyzed using Electroflo while the enclosure which houses these boxes can be analyzed using a third party code.

Results

The numerical analysis predicts a maximum velocity of .076 m/sec and a maximum temperature of 49.24 °C when the currents of 5 amps are input at three locations in the trace.

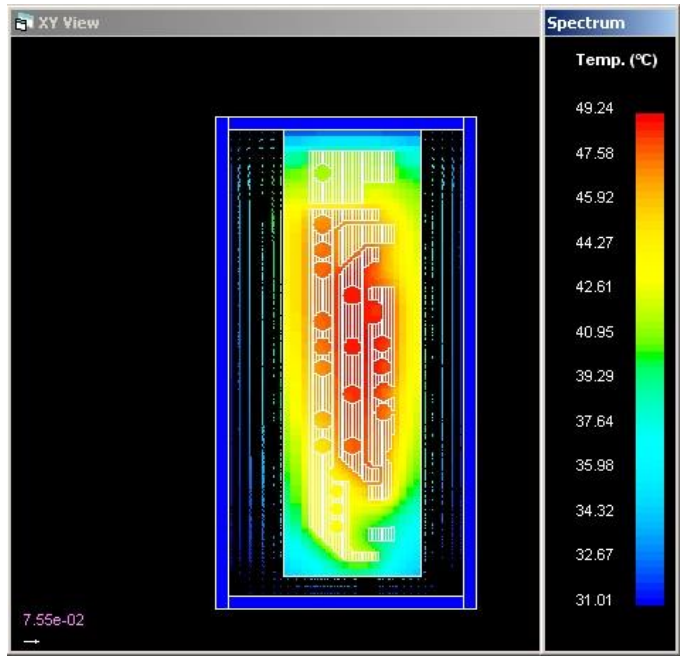

Figure 3: Temperature Distribution Single System Board and Enclosure

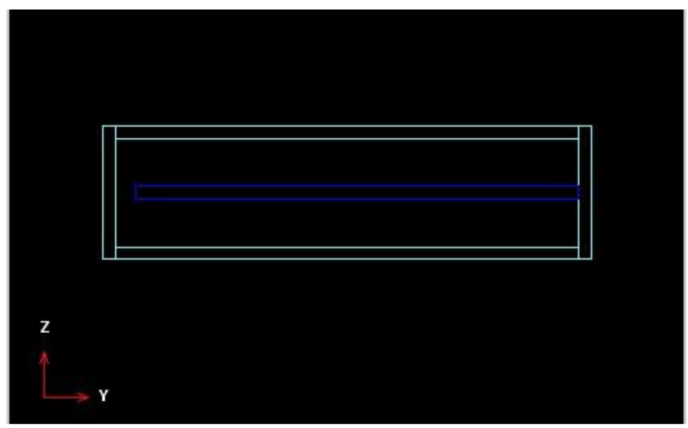

Figure 4: Enclosure model with board blanked out

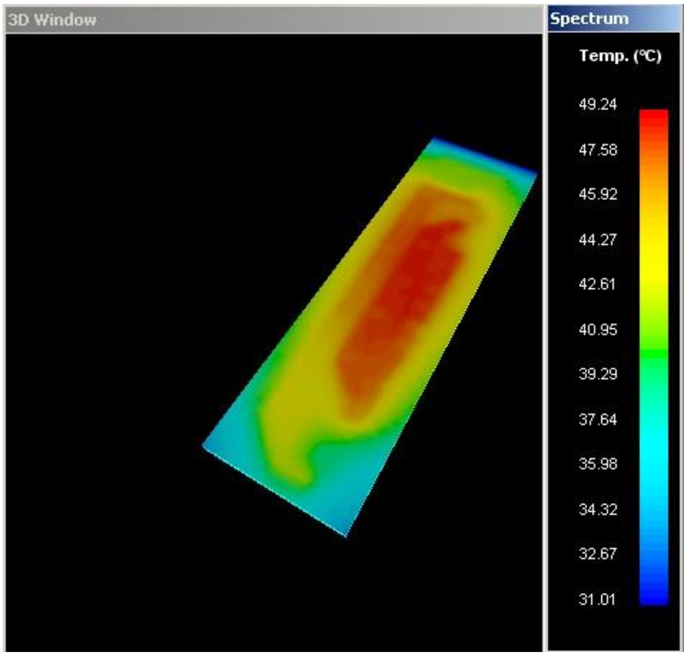

Figure 5: Circuit Board Temperature Distribution Running as a Separate System

Conclusions

This study points to a large class of electronics applications that require the coupled solution of heat transfer, flow and voltage fields. A multi system approach was demonstrated that can enhance the flexibility of modeling as well as accuracy and speed of calculations. The multi system approach can be used across networks and has a potential to integrate different software packages each working a sub section of the model. The procedure was demonstrated through the solution of an illustrative electronic box with a board with Joulean heating in copper traces. 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.

References

1. Zandi, B., et. al., "Analytical and Experimental Investigation the Natural Convection Cooling of Television Receivers", University of Tennessee Press,

2. Zandi, B., "Novel Approaches in the Thermal Management of Electronics Involving Coupled Electrical, Thermal and CFD Analysis", Ph.D. Dissertation, University of Tennessee, 2005.

3. Doerstling, B., "Thermal-Electrical Modeling of Electrical Subsystems", SAE Technical Paper Series, 1998.

4. Zandi, B., Lewis J. M., Lewis H., "Transient Coupled Thermal/Electrical Analysis of a Printed Wiring Board", ITherm Conference, June 2004.

5. Jackson, J. D., Classical Electrodynamics, 3rd Edition, John Wiley and Sons, Inc., 1998.

6. Patankar, S. V., Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, Washington, 1980.
7. Electroflo User's Manual, TES LLC 2005

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