SRC TR 88-18

Validation of a Thermal Model Using Infrared Thermography

by

C. Resch and M. Pecht

VALIDATION OF A THERMAL MODEL USING INFRARED THERMOGRAPHY

Cheryl Resch
Systems Research Center

Michael Pecht
Mechanical Engineering Department
University of Maryland, College Park, MD 20742

ABSTRACT

The ability to accurately calculate the temperature profile of a printed wiring board (PWB) is necessary in determining the reliability of the PWB. Calculating temperatures of electronic components on PWBs requires that models be developed and tested for their validity. Infrared thermography provides one method of measuring the temperature profile of a PWB. Using an infrared camera, a thermal "snapshot" is taken of the PWB where the colors on the snapshot represent ranges of temperatures.

The temperature profile of a conductively cooled PWB is modeled using the University of Maryland RAMCAD system and validated using both infrared thermography and thermocouples. The two sets of measurements are compared and the validity of using infrared thermography to determine the accuracy of a thermal model is discussed.

KEY WORDS : Infrared Thermography, Temperature Measurement, Thermal Simulation

INTRODUCTION

The University of Maryland RAMCAD is a computerized system of integrated tools used to determine the reliability of electronic systems, the location of unreliable components, and the reliability effects of the component types, thermal conditions, fatigue, and shock and vibration conditions. RAMCAD is best used in the design stage, so that reliability can be designed-into the product.

The temperature of electronic components on printed wiring boards (PWBs) is one of the important parameters in the determination of the reliability of a PWB. The reliability of a component is directly related to the component's operating temperature and thus the thermal profile of the entire PWB assembly. Validating the thermal analysis calculations package is therefore very important.

Since most PWBs have hundreds of heat dissipating components, the governing equations for heat transfer cannot generally be solved directly. They must be solved by approximate numerical methods, such as finite-difference. These numerical methods must therefore be checked for their accuracy against experimental results. Also, the material parameters, such as the thermal conductivity of the heat sink, used in the model are not necessarily accurate. These parameters must also be checked for their accuracy against experimental results.

Infrared thermography is a technique for determining the temperature profile of electronic PWBs. It is noncontact and will not change the thermal field while the measurement is being taken. Furthermore, the entire field of temperatures can be taken in minutes, unlike the traditional method of wiring a large number of thermocouples to take direct measurements.

BASIC CONCEPTS OF THE SIMULATION MODEL

The simulation model used in the University of Maryland RAMCAD system consists of a finite-difference model and a Gauss-Seidel iteration procedure. The finite-difference model solves the two dimensional heat conduction equation

$$q''' = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (1)$$

where q''' is the heat dissipated per unit volume, and k is the thermal conductivity of the

material for which the temperature profile is being calculated. The PWB is split into "nodes" for the analysis using the model. Equation (1) is modified to

$$T_{ij}\left(\frac{2k\Delta y\Delta z}{\Delta x}+\frac{2k\Delta x\Delta z}{\Delta y}\right) - T_{i,j+1}\frac{k\Delta y\Delta z}{\Delta x} - T_{i,j-1}\frac{k\Delta y\Delta z}{\Delta x} - T_{i+1,j}\frac{k\Delta x\Delta z}{\Delta y}$$

$$- T_{i-1,j}\frac{k\Delta x\Delta z}{\Delta y} - q_{i,j} = \text{residual} \qquad (2)$$

where Δx replaces ∂x, Δx^2 replaces ∂x^2, $q_{ij}/\Delta x\Delta y\Delta z$ replaces q''', and so on. In equation (2), $q_{i,j}$ represents the heat into node i,j from the electronic components on the PWB. When the residual in equation (2) becomes sufficiently close to zero, the solution has converged. Equation (2) is applied to every node through many iterations. After the equation is calculated for a node, the current value of $T_{i,j}$ is updated using the value of the residual. If the residual is positive, $T_{i,j}$ is too large, so $T_{i,j}$ is made smaller, and vice versa. $T_{i,j}$ is updated using the following equation

$$T_{i,j,new} = T_{i,j} - \frac{\text{residual}}{\left(\frac{2k\Delta y\Delta z}{\Delta x}+\frac{2k\Delta x\Delta z}{\Delta y}\right)} \qquad (3)$$

The conductively cooled PWB has cold plates attached to two of its edges. These edges are modelled using constant temperature boundary conditions. The other two edges are generally electrical connections, and are modelled using insulated boundary conditions.

Many aspects of this model must be checked for its accuracy. The value that the residual must obtain for "convergence" and the size of the nodes are two numerical properties whose accuracy is unknown. Material properties which are used in the model which must be checked for their accuracy are the cold plate temperatures and the thermal conductivity of the heat sink. The assumed boundary conditions are another factor whose validity must be checked.

BASIC CONCEPTS OF INFRARED THERMOGRAPHY

Infrared is a form of electromagnetic radiation, emitted by all physical matter at temperatures above absolute zero. Visible light radiation has wavelengths from approximately 0.4 μm to 0.7 μm. Infrared radiation has wavelengths from approximately 0.7 μm to 1000 μm. The temperature of any body above absolute zero is dependent on the peak wavelength of the radiation emitted from it. This dependence is the basis for the use of infrared temperature measurement. Most of the peak wavelengths are in the infrared range, while the body must be at about 5555 K for its peak wavelength to be in the visible light range. For all practical purposes then, to determine the temperature of a body based on the wavelength of the radiation it is emitting, an infrared detector is required. The correlation between wavelength and temperature is called Planck's spectral distribution of emissive power and is given as

$$e_{\lambda b} = \frac{2\pi C_2}{\lambda T^5\left(e^{c_2\lambda/T}-1\right)} \qquad (4)$$

where C_1 and C_2 are constants whose values are 0.59544×10^8 W $\mu m^4/m^2$ and 14388 μm K respectively.[2] Here, $e_{\lambda b}$ is the radiation energy emitted by a black body at wavelength λ.

Objects actually emit radiation in a spectrum around its peak wavelenth. Integrating equation (4) from λ=0 to ∞ the following equation is obtained for the total radiation from a black body.

$$e_b = \sigma T^4 \qquad (5)$$

where σ is the Stefan-Boltzman constant, 5.67×10^{-8} W/m^2 K^4

Real bodies emit a fraction of the black body radiation, and this fraction is called the emissivity. The amount of radiation emitted is determined by multiplying e_b in equation (5) by the emissivity, which is a number between zero and one. Hence, to use an infrared camera, the emissivity of the surface must be known.

Radiation directed at an object's surface is reflected, transmitted, or absorbed. Radiation absorbed is subsequently emitted. PWBs are made of materials which transmit negligible infrared radiation, so that the total radiation heat transferred from the object is

$$e = (\varepsilon\sigma T_o^4 + \rho\sigma T_a^4) \quad (6)$$

where ε is the emissivity of the object, and ρ is the reflectivity of the object. The emissivity and reflectivity of an object are the fraction of total radiation being emitted and reflected, respectively. Since transmission is neglected, $\varepsilon + \rho = 1$ so that

$$e = (\varepsilon\sigma T_o^4 + (1 - \varepsilon)\,\sigma T_a^4) \quad (7)$$

where e is the radiation energy being sensed by the camera, T_o is the temperature of the object, and T_a is the ambient temperature. This is the relation used by the infrared temperature measurement system. The first term is the radiation emitted by the target object and the second term is the radiation emitted by the surroundings.

For an object to be properly viewed, it must emit a large portion of the total radiation sensed by the viewer, i.e. the first term on the right side of equation (7) should be much larger than the second term. It is desirable to have a surface which has a large emissivity. Reflective or metallic surfaces should therefore be covered with a high emissivity material. For use in PWBs, where the different components can have very different values of emissivity, it is preferred that the entire PWB to be covered with a high emissivity material.

EXPERIMENTAL SET UP

In conduction cooling of PWBs a heat sink of high conductivity material is attached to the board. Cold plates are attached to the edges of the heat sink, and a cooling fluid such as freon or water flows through them. In the experiment, the PWB is made of is highly conductive composite material which serves as the heat sink. The edges of the composite board are curved and pointed so that the heat does not gather at the ends (there is no sudden discontinuity at the ends), and so that the heat sink only needs to be tightly clamped to the cold plates on one edge of the board.

The board is 6" by 6", and has two 2" x 5" flat resistor packs mounted symmetrically on each side of the board for four total resistors. The circuit was set up with variable resistors in front of each of the component resistors, such that each component resistor had the same amount of current, and the power dissipation rate of each was the same. The resistors were connected to a variable voltage source, so the experiment could be performed at different voltages and power dissipation rates.

The two cold plates, one on each side of the board, are made of two 1 x 1 x 7 inch bars of aluminum with a 5/8 inch diameter hole through which water flows for cooling. Along one side of each aluminum bar is a slot large enough to fit the board and a wedgelock. The wedgelock was made for the assembly to ensure high, constant pressure between the board and the cold plate, so that the aluminum does indeed act as a coldplate and take all the heat from the board. The cold plates are connected to a water tap. Type K thermocouples were placed at each water inlet and exit piping, so that the temperature rise of the water can be directly measured, in addition to using the infrared scanner to measure the temperature of the aluminum coldplates. Twenty three type k thermocouples were distributed across the board.

EXPERIMENTAL PROCEDURE

The water flow through the cold plates was measured to be 8 liters/minute, which is well above the 5 liters/minute necessary for turbulent flow, so that there is sufficient heat transfer from the aluminum to the water. The inlet and outlet temperatures of the water were measured to be about 12°C at the inlet, and the outlet temperature varied from about 13°C to 14°C , dependent on the power dissipation rate.

The board and the cold plates were covered with masking tape for constant, high emissivity. The emissivity was measured by using the camera to measure the temperature of a dull, black object (ε=1), then covering the object with the masking tape. The emissivity entry on the infrared system was adjusted until the temperature reading matched the temperature reading without the covering. The emissivity of the masking tape was measured to be 0.93.

The temperature measurements were taken in 5 volt increments, from 20 volts to 40 volts. The readings were taken after the temperature had been steady for one minute. Thermocouple and infrared scanner temperatures were taken at the same locations by using a pointer that shows up on the video screen. The monitor displays the temperature at user positioned cross hairs. The cross hairs are moved to the pointer location, and the temperature at that location is read.

RESULTS AND DISCUSSION

Figure 1 shows a gray scale version of the infrared picture. The thermocouple and the infrared results agree within 10 %. The error in the results is small enough that it may simply be attributed to error in reading the measurements.

The simulation program was executed for the same conditions as the experiment. The thermal conductivity of the board is known to be 311 W/m °C in the x direction (across the board and perpendicular to the heat sinks), and 0.9 W/m °C in the y and z directions. The maximum temperature rise above the sink temperature for each voltage is graphed in figure 2 for each set of results. The sink temperature is taken to be 12°C in all cases.

As sample output, Table 1 shows the output from thermocouples and the center of the board and at the left side of the board for the thermocouple, infrared scanner, and software.

Table 1 - Sample Output, (°C)

	Voltage	Thermocouple	Infrared Scanner	Program
Left	20 V	17.4	17.8	16.5
	25 V	21.4	20.2	18.6
	30 V	24.2	22.4	20.6
	40 V	32.5	30.0	29.8
Center	20 V	19.1	21.4	20.9
	25 V	25.7	24.7	23.3
	30 V	31.8	31.1	30.2
	40 V	45.1	44.3	40.0

The thermocouple and infrared results agree well, within 10 % , showing that infrared thermography is an accurate method for measuring the temperature profile of PWBs. The results from the software agree reasonably well with the measured results, but not quite as well as desired. As shown in figure 1, the temperature of the board just next to the cold plates is 2-3 °C higher than the temperature of the cold plate. The wedgelocks did not work as they were modelled in the program; the heat did not flow from the board to the cold plates as expected. The thermal contact resistance between the board and the cold plate is very high, and should be modified in the software to better reflect the actual value.

CONCLUSIONS

Infrared thermography can produce results of the same accuracy as thermocouples in measuring the temperature of powered PWBs. Using infrared thermography is quicker than using thermocouples to determine the temperature profile of the PWB. Rather than read the thermocouple outputs one by one, the temperatures across the entire board can be measured at one time with the infrared camera and the video output.

It is much easier to see hot spots and trends in the temperature profile using a thermal picture. If a PWB is malfunctioning, the cause of the malfunction may be seen using infrared thermography. Since it has been shown that infrared thermography is an accurate method of determining the temperature profile of a powered PWB, this method could have many applications in the design as well as the maintenance of PWBs.

Although infrared thermography has been shown to produce accurate experimental results, it should be noted that the temperatures obtained are those of the outside of the electronic component packages. Equations (1) and (2) calculate temperature profiles of the PWB substrate, i.e. the material underneath the electronic components. This discrepancy was avoided in the experiment described by using resistor packs of negligible thickness for heat sources rather than actual components. If this experiment were performed using actual electronic components, the calculated temperature profile must be modified to account for the temperature change between the substrate and the outside of the component packages. This modelling may become quite complicated and produce more inaccuracies. Also, reliability calculations require the temperature of the junction of the electronic component. The calculation of the junction temperature requires modelling of the inside of the component package, which cannot be verified experimentally. Although the calculation of the temperature of the outside of the component package can be checked for its accuracy, the final temperature calculation, that of the component junction, must be assumed accurate. There is therefore still a lot of work to be done in verifying temperature calculations used for reliability modelling.

ACKNOWLEDGEMENT

Partial support was provided by the University of Maryland Systems Research Center through the National Science Foundation Grant CDR85-00108

BIOGRAPHIES

Cheryl Resch received her B.S. in Mechanical Engineering and is currently a graduate student seeking an M.S. in Mechanical Engineering. Ms. Resch's area of expertise is in heat transfer mechanisms and the testing of circuit boards using infrared thermography. Ms. Resch a currently a fellow with the University of Maryland Systems Research Center.

Dr. Michael Pecht received an M.S. in Electrical Engineering and a M.S. and Ph.D. in Mechanics from the University of Wisconsin - Madison. He has worked as a consultant on the Astro I NASA space telescope project, and conducted research with Westinghouse Defense and Electronics Center on various mechanical engineering aspects of electronic packaging. Presently Dr. Pecht consults on issues related to the reliable design of printed circuit boards and is an Assistant Professor in the Mechanical Engineering Department at the University of Maryland.

REFERENCES

1. Siegel, Robert and John R. Howell. Thermal Radiation Heat Transfer, 2nd edition. Hemisphere Publishing Company, New York, 1981.

2. Schroeder, M.S., D.A. Lawton, T.M. Fertig, and T.F. Grapes. "Composite Heat Sink". Westinghouse Electric Corporation, Baltimore, MD 1987.

3. Hoffer, Kip O., Thomas W. Shaw, and Larry D. Robertson. "Electronic Module Design Evaluation by Thermal Imaging Analysis", Naval Engineers Journal, Volume 98, Number 3, May, 1986.

4. Wirtz, R.A., B.R. Hollworth, and H.A. Fuller. "An Infrared Thermographic Study of Convection in an Array of Surface Mounted Components", Proceedings, 5th Annual Electronics Packaging Conference, 1986.

5. Kallis, James M., Landon A. Strattan, and Thomas T. Bui. "Programs Help Spot Hot Spots", IEEE Spectrum, pp. 36-41, March, 1987.

6. Kallis, James M., Albert H. Samuels, and Roger P. Stout. "True Temperature Measurement of Electronic Components Using Infrared Thermography", Proceedings, 4th Annual International Electronics Packaging Conference, 1984.

FIGURE 1
Infrared Image

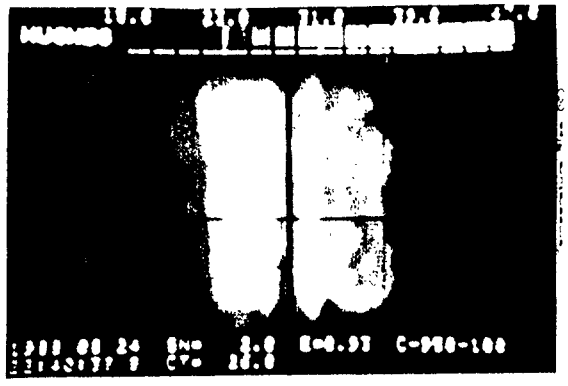


Figure 2

