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Thermal analysis on PCB using Galerkin approach / Mohd
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(4th International Conference On Modeling Simulation & Applied Optimization (ICMSAO 2011),
19-21 April 2011, Impiana KLCC Hotel and Spa, Kuala Lumpur)

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THERMAL ANALYSIS ON PCB USING GALERKIN APPROACH

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Abstract

This paper presents the analysis of temperature rise on PCB. Numerical solutions using Galerkin approach that is one of Finite Element Method (FEM) was used to study and analyze the temperature rise on PCB. Then, an algorithm has been developed using MATLAB. The PCB with four different width of copper is supplied with different range of direct current (DC) from 0.5 to 5 Amperes to capture the data by using FLIR i5 Infrared Thermal Imager. The data then compared with numerical result and obtain an error. In order to minimize the error, an analysis is done based on Galerkin approach with heat transfer film coefficient obtained from the experiment. The numerical results showed good agreement with the experimental results and it can be proved that the algorithm developed based on Galerkin approach can be applied to the thermal analysis on PCB.

Keyword: *Finite Element Method (FEM), Galerkin Approach, Heat Transfer, Printed Circuit Board (PCB).*

Nomenclature

A	area of cross-section of a one-dimensional element.
h	convection heat transfer coefficient.
k	thermal conductivity.
\mathbf{k}	stiffness (characteristics) matrix of complete body before incorporation of boundary conditions
$\rho^{(e)}$	length of one-dimensional element.
$\bar{\mathbf{p}}^{(e)}$	vector of nodal forces (characteristics vector) of elements e in global coordinate system
\mathbf{c}	vector of nodal forces of body before incorporation of boundary conditions.
q	rate of heat flow
\dot{q}	rate of heat generation per unit volume.
$\bar{\mathbf{q}}^{(e)}$	vector of nodal displacements (field variables) of elements e in local coordinate system.
$\bar{\mathbf{T}}$	vector of nodal temperature of the body before incorporation of boundary conditions.
T_b	temperature of the object's surface.

1. Introduction

The requirement of higher power density in many applications is grown widely which causes the current density in PCB increase constantly. With the miniaturization of modern electronic packaging the design of PCB has becomes increasingly dense. Thus, heat generation density is increasing and PCB becomes one of heat dissipating path. Hence, thermal management is one of the important considerations in construction of PCB[1]. In PCB design, heat is generated on copper conductor due to current flow. Heat generated can causes deposition of thermal energy in that copper which is associated Joule heating of the copper traces [2-3]. Heat flow, Q through conductor of PCB is represented by current input on the conductor. Q is proportional to the current, I and resistance, R_e . Resistance of conductor is measured at ambient temperature, T_∞ .

$$Q = I^2 R_e \quad \{1\}$$

The heat is then distributed and dissipated on the PCB and surrounding, which is called heat exchanger. This heat exchanger has occurred to equalize the temperature between PCB and surrounding [4]. There are three way of heat exchange process: convection heat exchange, radiation heat transfer and conduction heat exchange [5]. The PCB is heated up due to conduction process. Heat from the copper conductor is distributed away to the PCB then will heat up the surrounding air. The heat air is moved and carried energy away from the board. The energy is transferred to the air by convection while at the same time, the hot sections of the board radiate energy away from the board and transfer energy from the board to the surroundings.

The heat generated has potentially resulted in the PCB to fail and can be dangerous. It must rapidly and effectively divert to avoid the PCB damaged. Thus, it is required to design a PCB that fit the requirement and avoid this problem. Predictions of the temperature rise and heat distribution and dissipation on PCB become most important steps before designing a PCB. The challenges involved in modeling mathematical equation for PCB designed. It is required to consider entire parameters that affect the temperature rise on

PCB such as PCB size and thickness, number of traces that are involved in current carrying, traces separation, allowable temperature rise, copper volume percentage and trace cross-sectional area [1, 4]. Besides, other parameters that affected a temperature rise are heat transfer coefficient, h and thermal conductivity, k . However, conduction through the PCB is almost constant for different ambient temperature [1]. Thus, convection into the surrounding air becomes a critical parameter which affects the temperature rise on the PCB while radiation is assumed to have little impacts on the temperature rise.

This paper therefore analyzes the thermal on PCB by using Galerkin approach. A mathematical model using this approach is modeled for PCB designed by considers entire parameters. The PCB is designed follows from previous published work [2, 6-7]. Similar experiment is applied to this study. While acknowledging the parameters involved, an analysis has been done and validated the mathematical model. Once this mathematical model is validated, it is now possible to predict the temperature rise on PCB.

2. Finite Element Method

The FEM is an efficient method for solving heat distribution. Galerkin approach which is one of the approach in FEM can be used to derive the heat transfer problem [8]. This method is extremely crucial for the effectiveness of results. It can perform lots of calculations with various loading and meshing conditions [9]. To apply the FEM, it is required detailed information on the [10]:

- Geometry of the PCB designed.
- Material properties
- Location and quantity of heat generated
- Type and quantity of cooling available

By defined the entire information an actual problem can be modeled by reducing it to a mathematical relationship. There are a lot of methods to model this problem and study the heat distribution and dissipation on PCB. In this study, the method chosen is FEM via Galerkin approach while MATLAB software is used to develop an algorithm.

3. One-Dimensional Heat Transfer

For a one-dimensional heat transfer problem, the governing differential equation is given by

$$k \frac{d^2 T}{dx^2} + q = 0 \quad \{2\}$$

The boundary conditions are (combined heat flux and convection specified):

$$T(x=0) = T_0 \quad (\text{Temperature specified}) \quad \{3\}$$

$$k \frac{dT}{dx} l_x + h(T - T_\infty) + q = 0 \quad \text{on the surface} \quad \{4\}$$

board

The finite element procedure using Galerkin method for one-dimensional problems can be described by the following steps [8]:

Step 1: Idealize the PCB layer into several finite elements.

Step 2: Assume a linear temperature variation inside any elements "e".

Step 3: Derive the element matrices.

Step 4: Assembled equations.

The element matrices can be assembled to obtain the overall equations given by:

$$[K_3] \bar{T} + [K] \bar{T} = \bar{P} \quad \{5\}$$

where

$$[K_3] = \sum_{e=1}^E [K_3^e] = 0 \quad \{6\}$$

Thus,

$$[K] \bar{T} = \bar{P} \quad \{7\}$$

where

$$[K] = \sum_{e=1}^E \left(\frac{Ak}{\ell^{(e)}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} + \frac{hP\ell^{(e)}}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \right) \quad \{8\}$$

and

$$[\bar{P}] = \sum_{e=1}^E \bar{P}^{(e)} = \sum_{e=1}^E \frac{1}{2} (\dot{q}A\ell^{(e)} - qP\ell^{(e)} + hT_\infty P\ell^{(e)}) \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \{9\}$$

Step 5: The assembled equations {7} are to be solved, to find the nodal temperatures.

4. Experiment Apparatus and Method

A PCB has been designed to perform an experiment. The PCB is designed based on previous research [2, 11]. A single straight line of copper conductor is laying out on single sided FR4 PCB as shown in Figure 1. The current pass through the conductor is in range of 0.5A to 5A.

Table 1 shows the complete list of parameters on PCB design. The PCB is free standing at ambient temperature, 20 °C. Then, the temperature rises is recorded at the surface of PCB by using FLIR i5 Infrared Thermal Imager after 9 minutes being supplied with constant current. This is to ensure the temperature rise reach steady state condition.

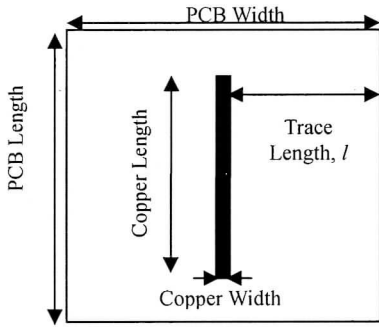


Figure 1: Front view of PCB design.

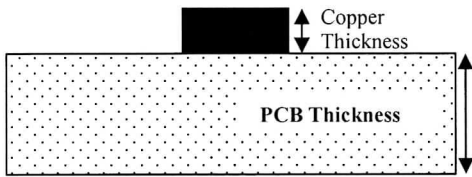


Figure 2: Side view of PCB design.

Table 1: List of parameters for PCB design.

Parameters	Value (mm)
Trace Length	37
Copper Width	1
Copper Length	240
Copper Thickness	0.03556
PCB Width	74
PCB Length	300
PCB Thickness	1.6

A temperature along the copper conductor is captured at both surfaces (top and bottom) of PCB as shown in Figure 3. It is found that the temperature is almost same for both surfaces due to small thickness of the PCB. The fact that the temperature variation across PCB thickness is very small which suggests that the location of the PCB traces along the thickness should not have much impact on the temperature rises [4]. Since the length of conductor is larger than the width, it can be assumed that no heat flowing along the length of conductor. However, the heat is distributed away from the edge of copper conductor to PCB and surrounding. Thus, a copper conductor is assumed as a heat source. The cross sectional area A of heat source now can be calculated using:

$$A = W \times T_{PCB} \quad \{10\}$$

where

W = width measured along the copper's length.

T_{PCB} = thickness of PCB.

In this project, the fixed width is set at 10 mm for the purpose of validation the Galerkin approach. The varied values of cross sectional area have a different value of heat transfer film coefficient.

Thermal conductivity, k is one of the parameters need to be consider. Two element of thermal conductivities in PCB design involved are thermal conductivity for copper and FR4. However, only thermal conductivity for FR4 is taking into account since the single layer PCB is used as sample work while copper is assume as heat source. The thermal conductivity for FR4 is $k_{FR4} = 0.00035$ watt/mm °C .

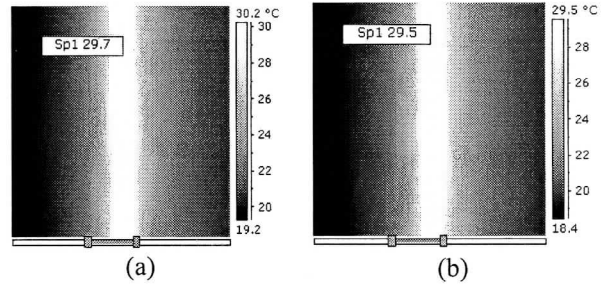


Figure 3: FLiR Thermal Imager measurement on top side (a) and bottom side (b) faces of PCB.

5. Result

The fact that the PCB is designed with single conductor at center of the PCB is to ensure the heat is distributed equally for both directions. Figure 5 shows the temperature distribution on the surfaces across the conductor if current supplied is 3A. The symmetrical shape of imaging profile proves that distribution of heat is symmetry. Thus, only single side of heat distribution direction on PCB is considered for the next analysis and comparison with manual calculation.

Figure 6 shows the temperature traced at the edge of conductor with various current supplied. Then, a quadratic equation obtained from using regression method is used to curve the plotted results. That equation is used to predict the initial temperature at the heat source with different DC supplied. Obviously, increasing the current will lead to temperature rise while resistance is fixed as equation {1}.

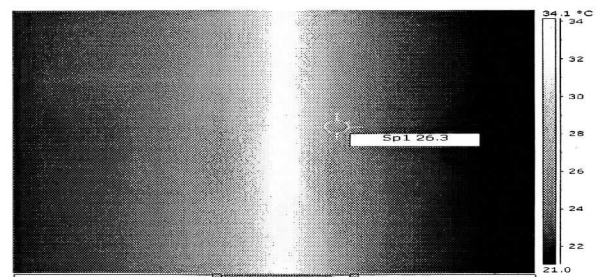


Figure 4: FLiR Thermal Imager measurement on center of top side faces of PCB.

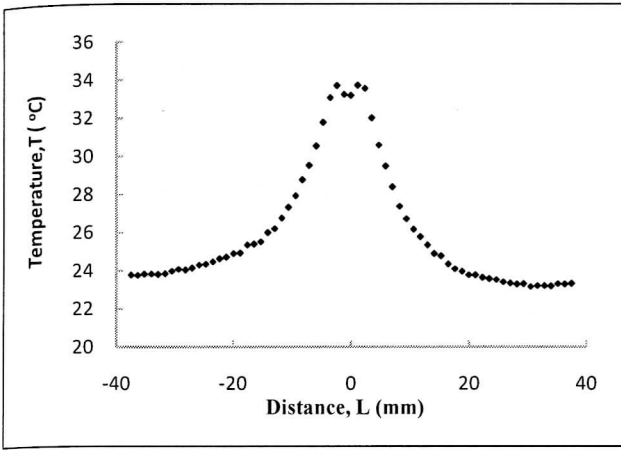


Figure 5: Infrared thermal imaging profile of PCB supplied with 3A DC.

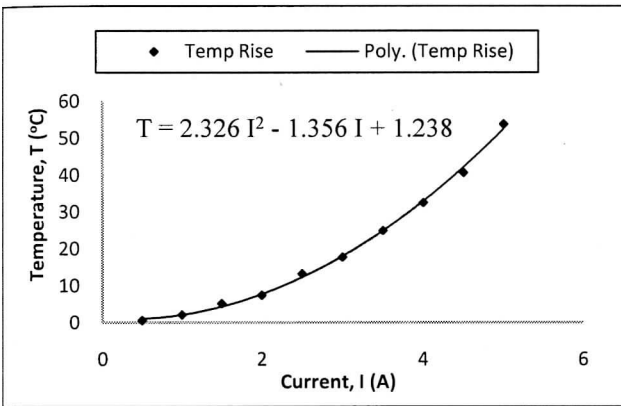


Figure 6: Temperature rise on PCB supplied with current, 0.5A to 5A.

6. FEM Analysis

The mechanism that cause the temperature rise on PCB is identified. Since most parameters is fixed, the heat transfer film coefficient, h is the main parameters to be focused while cross sectional area, A will be next. To find out the suitable heat transfer film coefficient, an algorithm has been developed using MATLAB. Result of calculation using Galerkin approach with suitable value of film coefficient and comparison with experimental data are plotted as shown Figure 7.

Comparison is done and an error obtained. Error is the temperature different between experimental data and calculation. The suitable error tolerance take into account is in range of ± 3 . To analyze the error, it was divided into three range of distance as in Table 2. The second range of distance from 5mm to 20 mm have a maximum average error while minimum average error can be traces on range from 20mm to total distance. Even though the error on second range is about six times higher compared to the minimum error, it is still in range of error tolerance. For future study, a modification of mathematical algorithm will be done continuously until minimum error is obtained.

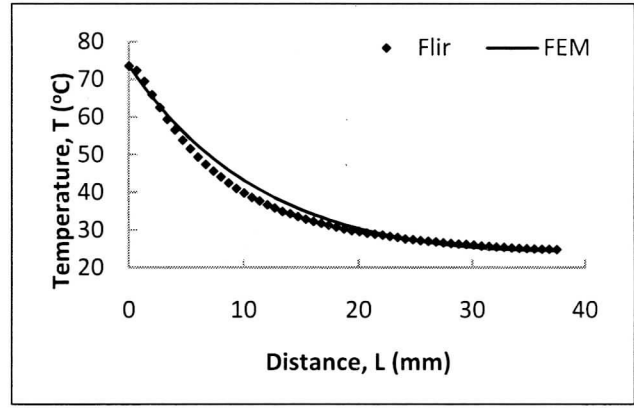


Figure 7: Comparison of Galerkin approach result versus infrared thermal imaging profile with current supplied is 5A.

The analysis of errors are summarized and shown in Table 2. The total average error is 1.324. From Table 2, it can be seen that the result of calculation has a minimum different with experiment data. This means that the approach is able to simulate the heat distribution and dissipation on PCB.

Table 2: Summarized error in different range of distance.

Distance, L (mm)	Average Error (°C)
$0 \leq L < 5$	1.325
$5 \leq L < 20$	2.363
$20 \leq L < 37$	0.3678

The convection film coefficient is required as input due to the free air convection involved. Although a fixed value is unknown, film coefficient with different value is applied until the results match with experimental values. The film coefficient is treated as combination of convection and radiation. The film coefficient obtained using algorithm is plotted against temperature of the copper conductor, as shown in Figure 8.

Then, an analysis is carried out for determining rate of heat dissipation by using linear regression of curve fitting. A linear relationship with temperature T is:

$$h = aT + b \quad \{11\}$$

where

$$h \text{ in unit of } W/mm^2 \text{ } ^\circ C$$

$$T \text{ in unit of } ^\circ C$$

$$a = 1 \times 10^{-6} W/mm^2 \text{ } ^\circ C^2, \text{ and}$$

$$b = 6 \times 10^{-6} W/mm^2 \text{ } ^\circ C$$

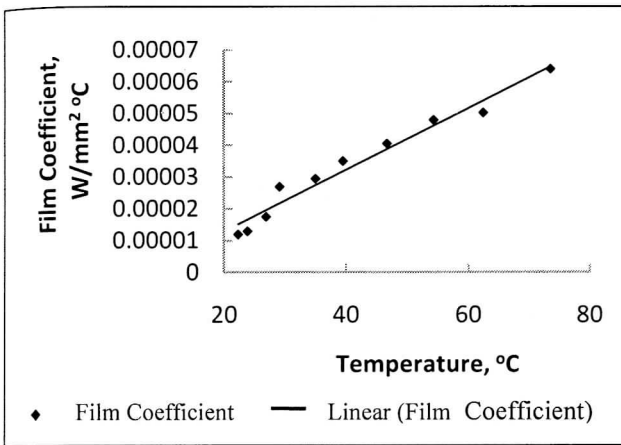


Figure 8: Heat transfer film coefficient at different temperature calculated using FEM.

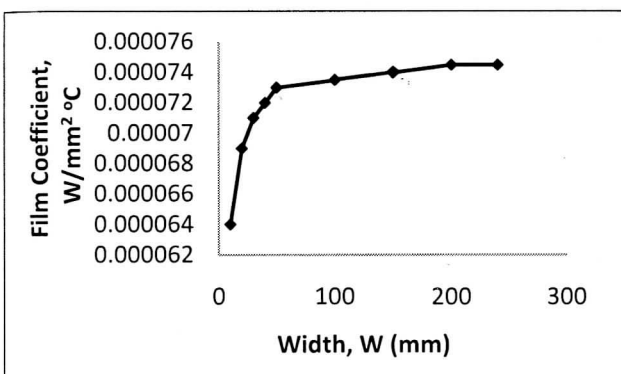


Figure 9: Heat transfer film coefficient at different width calculated using FEM.

Using the equation {10}, increasing the width will increase the cross sectional area since the thickness of PCB is fixed. By applying this cross sectional area into equation {8} and {9} it will affect the temperature rise due to the different value of heat transfer film coefficient. As shown in Figure 9, increasing the width will lead the heat transfer film coefficient. The heat transfer film coefficient at width = 10 mm is 0.000064 W/mm² °C while at width = 200 mm is 0.0000745 W/mm² °C. However, when the width is more than 200 mm, the heat transfer film coefficient is fixed at 0.0000745 W/mm² °C.

7. Consideration

The result of the experiment and simulation found that the temperature rise on PCB is caused by many parameters. The first critical parameter is the thermal conductivity of PCB while another critical parameter is heat transfer coefficient. A PCB commonly designed compact with electrical component and copper conductor. This design will decrease the free area on top and bottom PCB. Thus, it will affect the value of thermal conductivity and heat transfer coefficient.

The complex geometry of a PCB with different

material presents a technical challenge to the engineer in reducing it to an equivalent mathematical model [10]. For developing a mathematical model, it is required detail information about the PCB.

As a result, a simple PCB is designed as Figure 1 and Figure 2. Blank PCB with single copper conductor without any electrical component is used. This is to ensure the thermal conductivity and heat transfer coefficient is fixed while heat only comes from the copper conductor.

8. Conclusion

Interesting results are seen for both experiments and calculation using Galerkin approach. The PCB as work sample is modeled and designed for experimental part. Result is tabulated and presented. The relation between current supplied and temperature rise is obtained. Thus, a temperature rises can be predicted for any current supplied.

Finite Element Method via Galerkin approach used to solve heat distribution and dissipation is also discussed. The equation is derived and algorithm is developed using MATLAB. The film coefficient is obtained by using that algorithm followed by analysis of error. A minimum error was obtained by applying the film coefficient and other fixed parameters. Then, the Galerkin approach is verified with experimental values. Besides, the relationship between width and film coefficient is also obtained.

Since the Galerkin approach is verified, the method is able to simulate and predict the temperature rise on PCB with a different parameter. This method will bring a lot of benefit such as the time consuming, computational saving and reduce cost.

More investigations are required to study the effect of other parameters to the temperature rise. Besides, to predict more precisely the temperature rise, a two dimensional Galerkin approach is suitable to apply. This process will include analysis, verifications, and also redesign of both experimental and algorithm. It will be future work.

Acknowledgement

We wish to acknowledge Mr. Asri Din, Mr. Nizam Kamarudin, Mr. Kadri Md Saleh and Ms. Nur Huda Mohd Amin for their valuable discussion and suggestions; and FRGS fund for this project.

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