Prediction of Operating Temperature of Electronic Components on Printed Circuit Boards

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Abstract—The current study seeks to provide a perspective on the capabilities of the Laplace finite difference (LFD) method to predict operating temperatures of components of electronic systems. This paper presents a systematic assessment of the predictive accuracy of thermal analysis using LFD code for heat transfer of components mounted on a printed circuit board (PCB). The numerical algorithm is implemented in MATLAB that provides an estimate of the computational effort. The analysis methodology is presented using a case study. Using this methodology, a large calculation time reduction is achieved without losing accuracy. Results show that the predicted values were less than the given limit of 9 degrees Celsius. Accuracy of predicting component operating temperature depends on the component location on the PCB, air-flow velocity and flow model applied. Experimental measurement of component junction temperatures is recommended to enable a comparison between simulated values and actual measurements. The error estimated from the difference between measured temperature values and simulated values can help in strategic product design decisions and reliability predictions. The error estimate converges to zero after about 7 iterations as the predicted temperature converges to the theoretical temperature. Thus, the temperature profile is accurately predicted with the help of the proposed LFD-based algorithm.

Keywords— numerical analysis; Laplace finite difference method; printed circuit board (PCB) thermal analysis; component heat transfer; electronics thermal prediction

Article history: Manuscript received 28 August 2020; received in revised form 30 September 2020; Accepted 30 September 2020.

I. INTRODUCTION

OVER the last decade, the electronics industry is progressing quite fast in terms of thermal design practices from basic calculations applicable to simple systems to virtual prototyping with the help of the latest numerical predictive methods [1]. The manufacturing of electronic products is developing towards embedded systems at nano-scale or even finer than that. It is imperative that the modelling of heat transfer surfaces or temperature profiling of such high-density integrated components will be quite complex in the future.

The domain of power electronics based on semiconductor devices is also emerging rapidly. The junction temperature of these devices is of critical significance from a thermal management perspective [2]. Due to repetitive thermal cycling, cracks or other faults may appear in semiconductor devices due to differences in thermal coefficients of materials. Estimation of the temperature of these components is necessary for conditioning and control purposes.

Another important consideration of measuring the temperature of the power electronic circuits is the management of thermal issue due to the limitation of power dissipation [3]. An accurate estimation of spatial dynamic thermal profile with the help of miniature temperature detectors is an important area of research. Dynamic temperature control by guaranteeing that the temperature of the hotspots remains within the thresholds could be achieved by accurate temperature measurement of onboard sensors.

This research aims to determine the temperature distribution inside the printed circuit board (PCB) and to show the output based on the Laplace finite difference method using MATLAB coding. The significance of the study lies in solving the complexities involved in heat transfer modelling of miniature electrical components on PCBs. The previous research work in this regard proposed numerical methods for predicting the temperature profile of the circuit components with reasonable accuracy. The current study optimizes these solutions with the help of derivation of temperature estimates from Laplace equations, and then numerically solving the problem with the help of algorithmic implemented in the MATLAB.

II. LITERATURE REVIEW

Consider a simple dynamic heat transfer model of the electronic circuit embedded on the PCB modelled by [4]. For solving such problems, the application of numerical methods to model the thermal dynamics of the electronic equipment on the PCB has increased due to the rise in computational powers [1]. The algorithms like Computational Fluid Dynamics (CFD) provide a realistic approach for heat transfer for analysis of the modern electronic circuits. The production of a design perspective for prediction algorithms for operating temperatures of the electronic components is more important than its prediction accuracy. The design productivity concerning the algorithmic approach has been considered in detail for CFD for the last five years, particularly in the domain of preprocessing and postprocessing capabilities. Moreover, the constraints imposed on the CFD analysis in typical electronic circuits cooled by various methods are quite complex. Despite the increase in the computational powers, the discretization constraints still limit modelling of the lengthy scales from micro to meter at different levels by application of a unified model. Due to the presence of large-sized grids and meshes, the computational power will be large to solve the discrete disparities. It is also possible to reduce or minimize the requirement of detailed geometry modelling of the components with the help of Compact Thermal Modeling (CTM) methodologies [5] [6] [7]. This approach relaxes the constraints of discretization but still is far away from the ideal solution due to the impact of the local flow field features that affect the computational complexity. The numerical prediction methods like the Jacobi method of solving the Laplace finite difference (LFD) equation of steady-state thermal conditions [8] also provide useful insight into heat transfer modelling of electronic components on PCBs.

According to Eveloy and Rodgers, a considerable research effort has been focused on the numerical prediction of the temperature of electronic components in PCBs [9]. Some researchers use compare numerical estimates and experimental measurements [1] [10]. Presently several CFD simulation software has been developed to predict thermal behaviours of electronic components in PCBs [11] [12]. Other design software such as Solid CAM, Solidworks, Abaqus, Multisim and Matlab/ Simulink has been used to carry out CFD simulation of electronic components of PCBs.

In a research carried out in 2003, Eveloy, Rodgers and Hashmi predicted temperatures of electronic components and assessed the accuracy of prediction by comparing the estimates with experimental results [13]. They found out that accuracy of the predictions was about 35% and recommended that for design purposes, numerical predictions should be supplemented with experiments to determine the level of accuracy [9]. The researchers however noted the importance of numerical predictions in the intermediate design phases as efficient, cost-effective and flexible [13].

In another research carried out in 2004, Eveloy, Rodgers and Hashmi used CFD analysis to predict heat transfer in transient board-mounted electronic components. The temperature and power dissipated were estimated and measured at the surface of PCB and junctions. The researchers found out that the temperatures and power were accurately predicted signifying that CFD analysis could be useful in determining component thermal behaviours and in optimizing the new assembly process [1].

In 2005, Eveloy, Rodgers and Hashmi researched prediction accuracy of numerical heat transfer estimates of electronic components mounted on PCBs exposed to free convection. Measurement of surface temperatures was carried using thermal test chips and infrared thermography. The measured temperatures were compared with simulated values. Their results showed that the temperatures predicted were within the limits of ±5OC which was a 7% difference, irrespective of the location of the component within the PCB [10].

In 2019, Bahiraei et al. [11] carried out a CFD analysis of hydro-thermal attributes of green nano-fluid electronic components. They investigated the effects of drop shapes and found out that an increase in concentration and velocity reduced the temperature of heating surfaces. They found out that nano-fluid has better merits in cooling electronic components in heat sinks compared to pure water. This research shows that advances in numerical prediction of thermal behaviours of electronic components have resulted in effective cooling.

In 2020, Sokmen and Karatas performed CFD and experimental analysis of heat and temperature of components in PCB in LED junctions. The finite volume method was used to analyze temperature distribution on the components in software known as FloEFD 2019 [12]. The researchers found out that the highest light output was reached with the current of 65 mA. They also noted that the components on PCB had indirect effects on light output at the junctions [12].

In 2013, Chen et al. proposed an innovative real-time temperature measurement method for power electronic devices that manages the temperature of MOSFETS increasing due to thermal ageing effects. Their proposed model incorporates the updated electrothermal models of power modules into digital controllers [2]. The predicted device temperature with the help of threshold voltage measurement is used to correlate with thermal ageing of devices [2]. The developed adaptive technology could be applied to a wide range of power electronic devices.

In 2019, the research work of Tannous et al. considered estimation of the temperature of the power electronic circuit. They used the concept of duality between thermal and electrical systems for thermal modelling of circuits [3]. An optimal temperature measurement strategy is employed with the help of the Kalman filter [3]. By maximizing the trace of the observability index, the optimal placement of the temperature sensors is obtained.

III. METHODOLOGY

The methodology in this research is theoretical modelling of the temperature profile of electronic components embedded on PCBs. For this purpose, we will employ Numerical methods and suitable approximations to arrive at the solutions in the form of the required estimate of the physical states of the electronic components. The methodology includes the derivation of temperature estimates from LFD equations that model the given mesh of the electronic circuit into its sub-components in different coordinate dimensions. The problem could be solved in 2-D or higher-dimensional vector fields depending on the complexity of the PCB and the accuracy of the temperature profiling required. The problem definition will begin from the basics of the LFD equation that will be divided into 2-D components. Based on the PCD model, the temperature profile in the 2-D space will be estimated. The mesh is divided into different variables that indicate the dimensional space of the model used for the temperature profiling of the electronic components. The numerical algorithm is implemented with the help of MATLAB coding. The temperatures were iterated from initial values of zero degrees Celsius using the temperature equations derived from Laplace equations.

A. Problem Definition

The performance of a PCB with numerous components spread into 20 parts is greatly dependent on the processor temperatures. The processor is located at the centre of the plate since the components are very sensitive to its temperature. Acceptable performance occurs if and only if the processor temperature is less or equal to 9 degrees Celsius. The temperatures at the edges are known and are as shown in Figure 1. It is required that it be determined by the use of LFD if its performance is within acceptable limits or not. The importance of the current study lies in the prediction of the temperature of the electronic components on the PCB by using numerical methods based on LFD. The significance of temperature profiling lies in the assessment of the health condition of the PCB. If the electronic components are getting heat-up due to faults or inadequate cooling, the temperature profile will show the hotspot conditions at the place of fault. Moreover, it will predict the temperature at different points on PCB for comparison of effect generated due to fault.

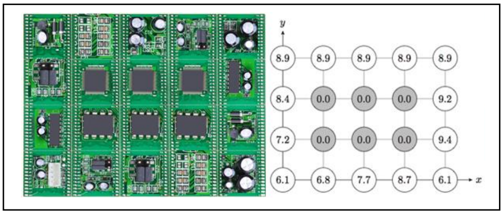

Fig. 1. PCB with components and defined edge temperatures

B. Derivation of Temperature Estimates

The LFD equation is given below.

$$\nabla^2 f = 0 \qquad (1)$$

where,

f= A given physical quantity that could be temperature or heat flux depending on the problem under consideration. In the given case study, it denotes the temperature of the electronic components. This is further expressed in terms of its coordinate components in the 2-D space as follows:

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0 \qquad (2)$$

Therefore, the 2D form of LFD is given by Equation 3.

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0 \qquad (3)$$

Substituting *f* with temperature, *T*, as the given physical quantity, we have Equation 4.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \qquad (4)$$

Equation 4 is further explained in terms of Equation 5. This is the 2-D version of the LFD equation for invariance of the temperature profile for electronic components on PCB.

For an equally spaced mesh shown in Figure 2, we have the points given as W, X, Y, Z with the centre being R.

From Equation 4 we have the following approximations based on the mesh in Figure 2.

$$\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) \cong \frac{1}{\Delta X}\left(\frac{\Delta T}{\Delta X}\right)$$

$$\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) \cong \frac{1}{\Delta Y}\left(\frac{\Delta T}{\Delta Y}\right)$$

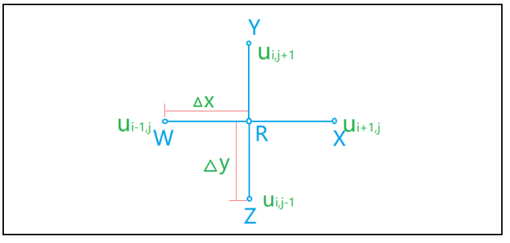

Fig. 2. Equally spaced mesh showing 4 points

From these approximations, we can find $\frac{\Delta T}{\Delta X}$ and $\frac{\Delta T}{\Delta Y}$ in terms of node temperatures.

Along the horizontal axis, the summation of all $\frac{\partial^2 T}{\partial x^2} = 0$

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\Delta X}\left(\frac{\Delta T}{\Delta X}\right) = \frac{1}{\Delta X}\left(\frac{T_W - T_R}{\Delta X}\right) + \frac{1}{\Delta X}\left(\frac{T_X - T_R}{\Delta X}\right) = 0$$

$$\frac{1}{\Delta X}\left(\frac{T_W - T_R}{\Delta X}\right) + \frac{1}{\Delta X}\left(\frac{T_X - T_R}{\Delta X}\right) = 0$$

$$\frac{1}{\Delta X}\left(\frac{(T_W - T_R) + (T_X - T_R)}{\Delta X}\right) = 0$$

$$\frac{(T_W - T_R) + (T_X - T_R)}{(\Delta X)^2} = 0 \quad (5)$$

Similar expression along the vertical axis gives

$$\frac{(T_Y - T_R) + (T_Z - T_R)}{(\Delta Y)^2} = 0 \quad (6)$$

Combining the two, we have

$$\frac{(T_W - T_R + T_X - T_R)}{(\Delta X)^2} + \frac{(T_Y - T_R + T_Z - T_R)}{(\Delta Y)^2} = 0$$

$$\frac{(T_W - 2T_R + T_X)}{(\Delta X)^2} + \frac{(T_Y - 2T_R + T_Z)}{(\Delta Y)^2} = 0 \quad (7)$$

$$\frac{(T_W - T_R)}{(\Delta X)^2} + \frac{(T_X - T_R)}{(\Delta X)^2} + \frac{(T_Y - T_R)}{(\Delta Y)^2} + \frac{(T_Z - T_R)}{(\Delta Y)^2} = 0 \quad (8)$$

For equal distances between the points, $\Delta X = \Delta Y$. We multiply Equation 8 by $(\Delta X)^2$ to give Equation 9.

$$(T_W - T_R) + (T_X - T_R) + (T_Y - T_R) + (T_Z - T_R) = 0 \quad (9)$$

Temperature can be represented as shown in Equation 10.

$$T_W + T_X - 4T_R + T_Y + T_Z = R_R \quad (10)$$

where,

T_W, T_X, T_R, T_Y and T_Z = temperatures at W, X, R, Y and Z. R_R= Residue.

The optimal solution occurs when R_R=0 as shown in Equation 11.

$$T_W + T_X - 4T_R + T_Y + T_Z = 0 \quad (11)$$

From Equation 11, we can obtain temperature, T_R, at the centre, as shown in Equation 12.

$$T_R = \frac{T_Y + T_Z + T_W + T_X}{4} \quad (12)$$

C. MATLAB Coding

MATLAB coding was done by defining inputs and outputs. The inputs included the number of nodes in the horizontal (x) direction which was 5, number of nodes in the vertical (y) direction which was 4, tolerance level which was 1e-6, errors which were limited to 1, iteration counters (N) and matrix of initial and boundary conditions. After 33 iterations there was convergence to the acceptable tolerance level and readings were taken from MATLAB.

Results and Discussions

The results of the study are based on the computational fields obtained from MATLAB coding. The values of the operating temperature of electronic components on the PCB and the value of error at each iteration are shown in Figures 3 and 4, respectively. The temperatures obtained were lower than 9 degrees Celsius. The highest temperature predicted in the central nodes was 8.666 degrees Celsius.

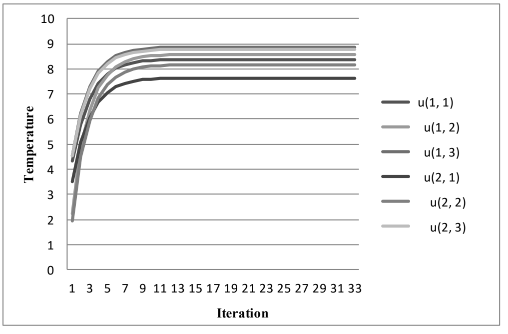

Fig. 3. The values of temperature of electronic components on PCB

Figure 3 shows the temperature profile of different nodes in the mesh of the PCB. Dividing the mesh into 3D space, we have different coordinate points for which iterations converge to a definite temperature. The graph shows that after 7 iterations, the prediction of the temperature of the given node point stays almost constant which shows fast convergence of the numerical algorithm.

Figure 4 is produced by comparing the temperature predicted at each iteration to the real temperature obtained from the reference method. Figure 4 shows the value of error at each iteration of the algorithm proposed in this study. The error reduces significantly near iteration number 7 as obvious from the trend of the temperature prediction in Figure 3 also. The algorithm is fast converging to the actual value after the 7th iteration after which the error practically becomes zero. Thus, the performance of the proposed algorithm is satisfactory in predicting the temperature of the electronic components in a reasonably fast manner for complex PCBs.

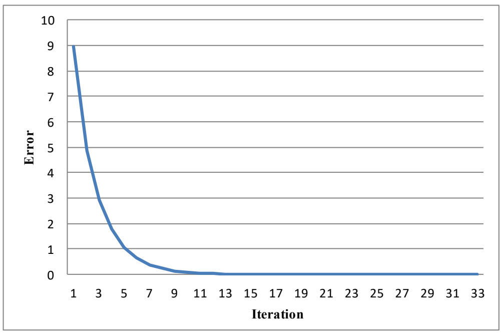

Fig. 4. The value of error at each iteration

Figures 5 and 6 graphically illustrate the results. Graphical output is given in 3D as shown in Figure 5, where the floor represents the nodes in x and y directions while the z-axis represents temperatures. Figure 6 shows a simplified output from the 3D graph.

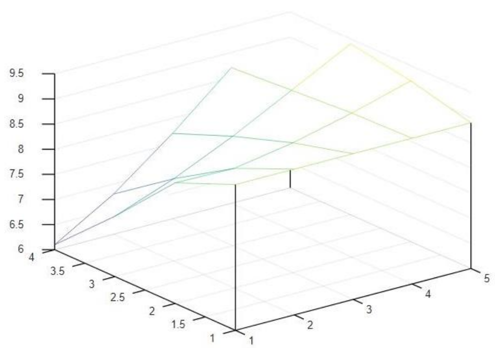

Fig. 5. Graphical output with z-axis temperature

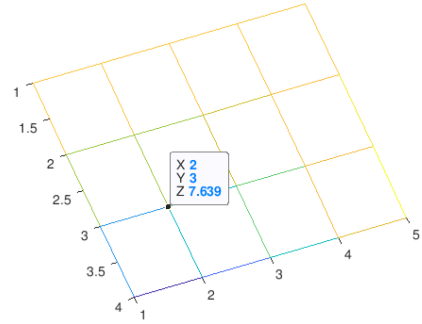

Fig. 6. Simplified graphical output

Temperatures were lower than 9 degrees Celsius and tended to be high at the nodes that were close to the edges with high temperatures. The highest central temperature was found to be 8.8666 degrees Celsius at node U13 as shown in Figure 7. The lowest central temperature of 7.639 degrees Celsius occurred at node U21 adjacent to the edge with the lowest temperature. We compared the results with previous research [13] to ascertain the performance. The results obtained in our study agree with those previously obtained by Eveloy and Rodgers [13].

8.9000	8.9000	8.9000	8.9000	8.9000
8.4000	**8.3800**	**8.5807**	**8.8666**	9.2000
7.2000	**7.6391**	**8.1764**	**8.7858**	9.4000
6.1000	6.8000	7.7000	8.7000	6.7000

Fig. 7. The final values of the operating temperature of electronic components on PCB

V. CONCLUSION

The temperature distribution inside the printed circuit board (PCB) was determined with the help of LFD- based numerical algorithm implemented in MATLAB. Output based on Laplace finite difference (LFD) method was also presented. The operating temperatures predicted of electronic components on PCBs by the LFD show good agreement with solid and fluid heat transfer analysis, while much less calculation time is required compared to existing methodologies. Results show that the predicted values were less than the given limit of 9 degrees Celsius. It is recommended that for practical applications, this approach can be complemented with experimental approaches to determine its level of error and reliability in temperature predictions.

ACKNOWLEDGEMENT

The author would like to express his appreciation to the College of Engineering at AMA International University Bahrain for supporting this research.

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