ISSN: 2456-219X

Journal Of Mechanical Engineering And Biomechanics Volume 11 Issue 1 April 2026

FINITE ELEMENT THERMAL ANALYSIS OF A CIRCUIT BOARD UNDER STEADY-STATE AND TRANSIENT CONDITIONS

Mr. N. Raghuveer[1]
Y. Raja[2], C.H. Tarun[3], S.V. Kalyan Kumar[4], M. Abdul Wahid[5]

Assistant Professor ,Department of Mechanical Engineering
Pragati Engineering College (Autonomous)
(Affiliated to JNTUK)
Kakinada District, Surampalem -533437

[2,3,4,5]Students, Department of Mechanical Engineering
Pragati Engineering College (Autonomous)
(Affiliated to JNTUK)
Kakinada District, Surampalem -533437
Mail.Id: raghuveer.n@pragati.ac.in[1], Mail.Id: rajayejju545@gmail.com[2]
Mail.Id: tarunchenchala999@gmail.com[3], Mail.Id: sundarakalyan2003@gmail.com[4]
Mail.Id: wahidabdul450718@gmail.com[5]

ABSTRACT

Printed Circuit Boards (PCBs) in modern electronic systems contain multiple heat-generating components operating under both continuous and intermittent conditions. Accurate prediction of temperature distribution is critical for ensuring reliability and preventing thermal failure.

In this study, a PCB assembly containing three heat-producing chips is analyzed using the Finite Element Method (FEM) under steady-state and transient conditions. One chip operates continuously, while two additional chips operate intermittently with specified activation intervals.

1. INTRODUCTION

Electronic systems continue to increase in:

- Power density
- Functional integration
- Miniaturization

As a result, thermal management has become a critical aspect of electronic design.

PCBs serve three primary functions:

1. Mechanical support
2. Electrical interconnection
3. Thermal conduction path

Heat generated by semiconductor devices must be effectively dissipated to avoid:

- Component degradation
- Solder joint fatigue

- Parameter drift
- Premature failure

Reliability studies show that failure rates increase exponentially with temperature, emphasizing the need for accurate thermal modeling.

2. GOVERNING HEAT CONDUCTION THEORY

The thermal behavior of solids with internal heat generation is governed by the transient heat diffusion equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}$$

Where:

- T= Temperature
- ρ= Density
- C_p= Specific heat
- k= Thermal conductivity
- $\dot{q}$= Volumetric heat generation

This equation represents:

- Energy storage
- Heat conduction
- Internal heat generation

2.1 Steady-State Form

When a thermal system is subjected to constant heat generation and boundary conditions for a sufficiently long time, it eventually reaches thermal equilibrium. Under these conditions, the temperature no longer varies with time, and the transient term vanishes:

$$\frac{\partial T}{\partial t} = 0$$

At thermal equilibrium:

$$\nabla \cdot (k \nabla T) + \dot{q} = 0$$

No temperature variation with time occurs.

3. STEADY-STATE VS TRANSIENT ANALYSIS

3.1 Steady-State Analysis

Assumes:

- Constant heat loads
- Infinite operation time
- Thermal equilibrium

Useful for:

- Maximum operating temperature
- Long-term thermal evaluation

Limitation: Cannot capture short-duration peaks.

3.2 Transient Thermal Analysis

Includes time-dependent term:

$$\rho C_p \frac{\partial T}{\partial t}$$

Captures:

- Heating cycles
- Switching behavior
- Thermal lag
- Cooling decay

Essential for duty-cycled electronic components.

4. INTERNAL HEAT GENERATION MODELING

Heat generation in semiconductor devices arises from:

- Joule heating
- Switching losses
- Leakage currents

Volumetric heat generation is modeled as:

$$\dot{q} = \frac{P}{V}$$

Three chips considered:

- Chip 1: Continuous operation
- Chip 2: Active from 20.1 s to 40.1 s
- Chip 3: Active from 60.1 s to 80.1 s

This creates time-dependent thermal disturbance.

5. CONVECTIVE BOUNDARY CONDITIONS

Heat loss to ambient air is modeled using Newton's Law of Cooling:

$$-k\frac{\partial T}{\partial n} = h(T - T_\infty)$$

Where:

- h= Convective heat transfer coefficient
- $T_\infty = 22^\circ C$

Natural convection assumed.

This introduces nonlinear boundary behavior due to temperature-dependent h.

6. FINITE ELEMENT FORMULATION

The temperature field is approximated as:

$$T = \sum N_i T_i$$

Substituting into governing equation gives:

$$[C]\{\dot{T}\} + [K]\{T\} = \{F\}$$

Where:

- [C] = Capacity matrix
- [K] = Conductivity matrix
- {F} = Heat load vector

Steady-state neglects [C] term.

Transient includes full matrix equation.

ISSN: 2456-219X
Journal Of Mechanical Engineering And Biomechanics Volume 11 Issue 1 April 2026

7. MATERIAL MODELING

PCB and chips modeled as homogeneous isotropic materials.

Material parameters:

- Density
- Specific heat
- Thermal conductivity

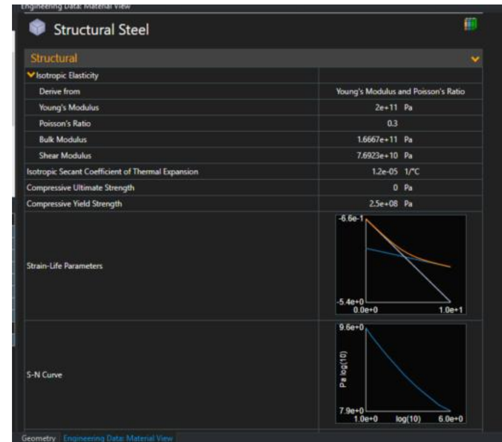
Two materials compared:

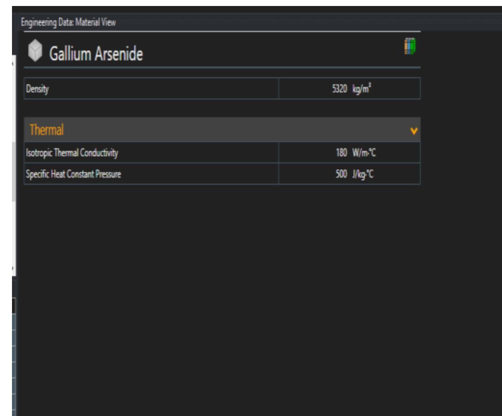
Material	Steady-State (°C)	Transient (°C)
Structural Steel	273.67	188.71
Gallium	208.86	184.39

Differences arise due to variations in:

- Thermal conductivity
- Heat capacity
- Thermal inertia

Material Composition and Thermal Heterogeneity





A PCB assembly is inherently a heterogeneous material system, composed of different solids with widely varying thermal properties. The PCB substrate is typically a polymer-based composite material, such as epoxy glass laminate, which exhibits relatively low thermal conductivity, moderate density, and moderate specific heat capacity. In contrast, semiconductor chips are dense, compact solids with higher thermal

ISSN: 2456-219X
Journal Of Mechanical Engineering And Biomechanics Volume 11 Issue 1 April 2026

conductivity and lower thermal resistance paths to the PCB.

8. MESH AND DISCRETIZATION STRATEGY

Multi-zone mesh applied:

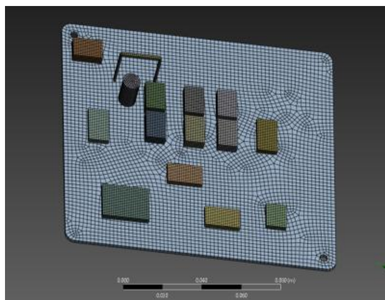
- Fine mesh (0.3 mm) in chip regions
- Coarser mesh (1.0 mm) in PCB

Justification:

High temperature gradients near heat sources require refined discretization.

Gradient-based refinement minimizes interpolation error.

geometric features, **material interfaces**, and **temperature gradients**.



Mesh

9. STEADY-STATE RESULTS

- Highest temperature at continuously operating chip
- Heat spreads laterally through PCB
- Maximum temperature determined by thermal resistance

Temperature contours confirm:

Localized hotspot formation
Gradual gradient reduction away from source

10. TRANSIENT RESULTS

Heating Phase:

- Rapid temperature rise in active chips
- Thermal lag in PCB substrate

Cooling Phase:

- Exponential-like decay
- Governed by system thermal time constant

Temperature probe plots show smooth transitions without numerical oscillation.

11. THERMAL TIME CONSTANT INTERPRETATION

Thermal time constant depends on:

$$\tau \propto \frac{\rho C_p V}{hA}$$

High thermal mass → Slow response
Low thermal mass → Fast response

Chips heat rapidly; PCB responds slowly.

12. GLOBAL ENERGY BALANCE

Transient behavior reflects competition between:

- Energy input
- Energy storage

- Energy dissipation

Heating occurs when input > removal Cooling occurs when removal > input

Consistent with first law of thermodynamics.

13. THERMAL COUPLING EFFECTS

Heat generated in one chip influences:

- Neighboring chip temperatures
- Board-level temperature distribution

Demonstrates importance of multi-chip modeling.

14. ENGINEERING SIGNIFICANCE

Combined analysis enables:

- Peak temperature prediction
- Hotspot detection
- Reliability assessment
- Design optimization

Steady-state alone is insufficient for intermittent operation.

15. VALIDATION OF THEORETICAL EXPECTATIONS

Observed behavior matches classical theory:

- Steady-state equilibrium
- Exponential cooling
- Distributed heat diffusion
- Convection-controlled decay

Confirms correctness of FEM formulation.

16. DISCUSSION

Key findings:

- Transient peaks exceed steady-state temperatures
- Thermal inertia significantly influences response
- Material selection strongly impacts temperature levels
- Linked steady-state/transient approach improves realism

17. CONCLUSION

This study presented a rigorous finite element thermal analysis of a PCB under steady-state and transient conditions.

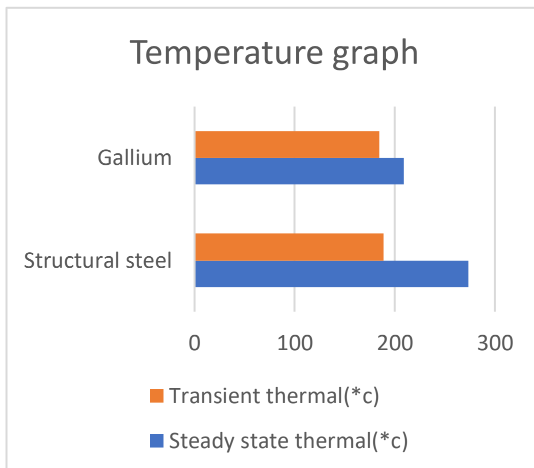
Major conclusions:

1. Steady-state analysis provides equilibrium baseline.
2. Transient analysis captures realistic switching behavior.
3. Thermal inertia governs temperature evolution.
4. Convective boundary modeling significantly affects results.
5. Material properties strongly influence peak temperatures.
6. Combined analysis approach is essential for modern electronics.

The methodology provides a reliable framework for thermal reliability assessment and PCB design optimization.

integration continue to increase.

S.No	Material	Steady state thermal(*c)	Transient thermal(*c)
1	Structural steel	273.67	188.71
2	Gallium	208.86	184.39



REFERENCES

1. Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S.
Fundamentals of Heat and Mass Transfer, 7th Edition.
John Wiley & Sons, 2011.
→ Core reference for heat conduction theory, convection boundary conditions, transient analysis, and thermal time constants.

2. Carslaw, H. S., & Jaeger, J. C.
Conduction of Heat in Solids, 2nd Edition.
Oxford University Press, 1959.
→ Classical reference for analytical heat diffusion equations and theoretical foundations.

3. Özisik, M. N.
Heat Conduction, 2nd Edition.
John Wiley & Sons, 1993.
→ Authoritative source on transient heat conduction, internal heat generation, and boundary value problems.

4. Holman, J. P.
Heat Transfer, 10th Edition.
McGraw-Hill Education, 2010.
→ Widely used reference for steady-state vs transient heat transfer and convection modeling.

5. Kreith, F., Manglik, R. M., & Bohn, M. S.
Principles of Heat Transfer, 7th Edition.
Cengage Learning, 2011.
→ Supports theoretical interpretation of conduction–convection coupling.

Finite Element Method & Numerical Heat Transfer

6. Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z.
The Finite Element Method: Its Basis and Fundamentals, 7th Edition.
Elsevier, 2013.
→ Fundamental reference for FEM formulation, capacity and conductivity matrices, and discretization theory.

7. Reddy, J. N.
An Introduction to the Finite Element Method, 3rd Edition.
McGraw-Hill, 2006.
→ Clear explanation of FEM applied to heat conduction problems.

8. Lewis, R. W., Nithiarasu, P., & Seetharamu, K. N.
Fundamentals of the Finite Element Method for Heat and Fluid Flow.
John Wiley & Sons, 2004.
→ Strong reference for transient thermal FEM and convection boundary treatment.

9. Bathe, K. J.
Finite Element Procedures.
Prentice Hall, 1996.
→ Numerical stability, time integration, and nonlinear boundary conditions.

Electronics & PCB Thermal Management

10. Lasance, C. J. M., & Poppe, A.
Thermal Management for LED Applications.
Springer, 2014.
→ Applicable to volumetric heat generation and electronic packaging.

11. Ellison, G. N.
Thermal Computations for Electronic Equipment.
Van Nostrand Reinhold, 1989.
→ Classic reference on PCB thermal modeling and internal heat sources.

12. Bar-Cohen, A., & Kraus, A. D.
Advances in Thermal Modeling of Electronic Components and Systems.
ASME Press, 1990.
→ Theory of electronic component heating and system-level thermal analysis.

13. Azar, K. (Ed.)
Thermal Measurements in Electronics Cooling.
CRC Press, 1997.
→ Supports interpretation of temperature distributions and transient behavior.

Convection & Natural Cooling

14. Churchill, S. W., & Chu, H. H. S.
"Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate."
International Journal of Heat and Mass Transfer, Vol. 18, 1975.
→ Basis for temperature-dependent natural convection coefficients.

15. Bejan, A.
Convection Heat Transfer, 4th Edition.
John Wiley & Sons, 2013.
→ Strong theoretical backing for natural convection modeling.