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# Numerical Investigation on the Influence of Substrate Board Thermal Conductivity on Electronic Component Temperature Regulation

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**ABSTRACT**

This study presents a detailed numerical analysis of substrate boards made from various materials (FR-4, Si cladding, and Cu cladding) with nine electronic components mounted on them. Each component is subjected to different heat fluxes, and the analysis covers both natural convection (NC) and forced convection (FC) modes of heat transfer at air velocities of 4m/s and 6m/s. The findings reveal that at an air velocity of 6m/s, using a copper cladding board significantly lowers the temperatures of the electronic components by 34$^0$C to 54$^0$C compared to FR-4 and Si cladding boards. Additionally, the copper cladding reduces the required air-cooling velocity by 2m/s and achieves a temperature reduction for the IC chips ranging from 3.50$^0$C to 13.12$^0$C. It is recommended to use an air velocity of 4m/s with copper cladding to minimize fan power consumption while maintaining component temperatures below 125$^0$C. These results provide crucial insights for thermal design engineers, aiding in the selection of appropriate substrate boards for effective thermal management of electronic components. The study emphasizes the benefits of copper cladding in distributing heat more uniformly, reducing energy consumption, and maintaining optimal operating temperatures. Furthermore, it suggests that placing high heat-dissipating components at inlet or outlet points can minimize thermal interactions and overall configuration temperatures. The research offers valuable guidance to the heat transfer community, particularly electronic thermal designers, by highlighting the importance of substrate material choice and component placement in enhancing the reliability and lifespan of integrated circuits (ICs). The comprehensive analysis and recommendations serve as a vital resource for optimizing thermal control strategies in electronic devices, ultimately contributing to improved performance and durability.

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## 1. Introduction

Effective thermal control plays a crucial role in optimizing performance and longevity of devices as most of the electronic devices lead to fail only because of rise in temperature parameter during operations. This work focuses on assessing the efficacy of heat sinks in dissipating heat from these chips, crucial for maintaining optimal operating temperatures. By exploring heat sink-driven cooling strategies, the aim is to enhance the overall thermal management of integrated circuits. This involves investigating the cooling efficiency and potential temperature reduction achieved through the utilization of heat sinks, contributing to advancements in technology and ensuring the sustained performance and reliability of integrated circuitry in various applications. Modern electronic devices face challenges in efficiently dissipating heat due to increased power density, degrading thermal interface materials (TIMs), and high-performance computing demands, with advancements like graphene-enhanced TIMs and liquid cooling offering solutions. Additionally, innovations such as vapor chambers, flexible heat pipes, and phase change materials (PCMs) are being integrated to manage heat in consumer electronics, batteries, and wearables, while eco-friendly cooling technologies and AI-driven thermal management systems are emerging to enhance efficiency and performance.

Anant *et al.,* [1,2] utilized distinct substrate boards in numerical simulations to regulate the temperature of integrated circuit (IC) chips effectively and selected the proper material for substrate board and selected proper PCM numerically. Rahman and Raghavan [3] used natural and forced convection on four heat sources. Dogan et *al.,* [4] explored rectangular heat source characteristics, finding optimal dissipation by placing max heat at entrance/exit. Yadav and Kant [5] conducted experiments on vertical PCB-mounted heat sources, proposing a Nusselt number correlation. Alves and Altemani [6] analyzed laminar forced convection and proposed a predictive superposition principle. Yusoff *et al.,* [7] used Fluent for numerical simulations on a PLCC mounted on a PCB, noting improved thermal performance at higher air velocities.

Narasimham [8] examined heat transfer from IC chips, emphasizing limitations and proposing alternatives like liquid immersion and heat sinks for enhanced dissipation. Pirasaci and Sivrioglu [9] empirically noted the improved dissipation at lower Reynolds numbers. He *et al.,* [10] explored flush-mounted heat source heat transfer on a horizontal channel with air, favoring high emissivity.

Yu *et al.,* [11] introduced a new adaptive thermal management method for electronic devices. The system uses bionic sweating to provide extra cooling as temperatures rise, achieving 80% of the cooling capacity of fixed systems. Key factors affecting the performance of this sweating cooling method are also explored. Liu *et al.,* [12] picks the best heat storing materials (PCMs) for various applications (0-100°C), explores improving heat storage and transfer, and reviews PCMs in electronics and battery cooling. Ajmera and Mathur [13] examined three heat sources mounted flush, considering both natural and mixed convection, suggesting strategic placement for optimal cooling. Chaurasia *et al.,* [14] numerically simulated six heat sources under mixed convection, observing a substantial temperature decrease. Bejan *et al.,* [15] explored design and thermal optimization across diverse systems using thermodynamics and heat transfer principles. Anant et al., [16,17] focused on thermal control of IC chips numerically. Shital *et al.,* [18-20] explains critical reviews on heat transfer enhancement in heat exchangers. Rahul *et al.,* [21-25] explain the investigation on Laser Welding Parameters on the Strength of TRIP Steel. Gadekar *et al.,* [26], Kamble *et al.,* [27], and Gadekar and Kamble [28] explained experimental study on gear EP lubricant mixed with $Al_2O_3/SiO_2/ZrO_2$composite additives to design a predictive system. Patil *et al.,* [29] used a water-based $Al_2O_3$nanofluid was used in this work to grind materials due to its outstanding convective heat transfer and thermal conductivity qualities. Cirillo *et al.,* [30] designed an elastocaloric device specifically aimed at the cooling of the electronic circuits and the results reveal that the device based on wires bending gives the best performances (+50 % as COP with bending rather than loading). Masselli *et al.,* [31] created 2D model optimized an elastocaloric heat exchanger with bending wires and air coolant. It investigated wire configuration and operating conditions for best performance (0.5mm spacing, 20cm length).

Most examinations have focused on cooling discrete heat sources under various heat transfer modes (natural/forced/mixed), with many researchers using similar geometries for the heat sources. Additionally, numerous studies have employed flush or protrude-mounted heat sources with 1D and 2D geometries, suggesting potential for exploring 3D protrude-mounted heat sources. Numerical analyses and optimization techniques have been adopted, and various hybrid cooling methods have been utilized for cooling heat sources. Therefore, this study emphasize to identify the optimal arrangement of IC chips through numerical means to effectively mitigate temperature levels and identify the substrate board material suitable for particular applications and temperatures the 9 symmetric and non-symmetric electronic components. The electronic components are mimicked with aluminum chip and the thermal conductivity of aluminum is considered.

## 2. Computational Approach for Diverse Heat Sink Configurations

The current examination focuses on analyzing the thermal and fluid dynamics of IC chips positioned at various locations on an SMPS board. ANSYS Workbench Design Modeler software predicts temperature and flow patterns of the IC chips subjected to forced convection with water as the coolant circulating within the cold plate. ANSYS Workbench employs the FLUENT solver to address governing equations of thermo-fluid flow, utilizing a steady-state laminar multiphase model. The entire numerical model is depicted in Figure 1. The present analysis is carried using natural convection heat transfer mode with assignment of 5HTC at the wall of solid IC chips. The adiabatic condition is created at wall domain by assigning ambient temperature of 25 during initialization. The assignment of heat source is given in terms of Watt in input to the volume of IC chip.

**Table 1**
Specification of Heat source configuration

| EC | L (mm) | W (mm) | H (mm) |
|---|---|---|---|
| MP1 (U1) | 35 | 35 | 4 |
| MP2 (U2) | 27 | 27 | 3 |
| MP3 (U3) | 15 | 15 | 4 |
| IC4 (U4) | 12.5 | 12.5 | 3 |
| IC5 (U5) | 19.65 | 6.5 | 3.43 |
| IC6 (U6) | 15 | 20 | 3.5 |
| MF1 (U7) | 12 | 20 | 3 |
| MF2 (U8) | 20 | 20 | 3 |
| MF3 (U9) | 20 | 20 | 3 |

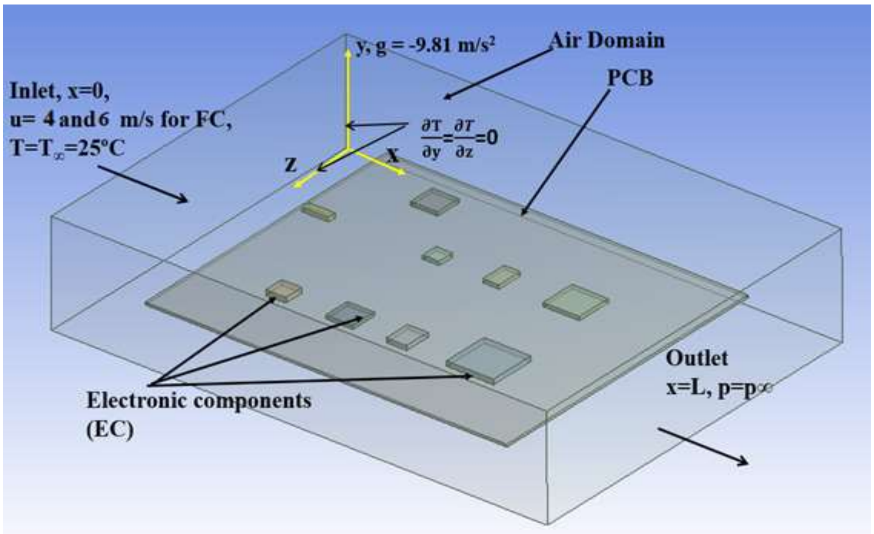



**Fig. 1.** Domain used

## 3. Boundary Conditions

The boundary conditions which are used in this research are given in following table, The boundary condition are considered as per the actual application , during the working condition of any electronic application ,the electronic components (IC chips, Processors, and Mosefts ) generate considerable amount of heat (Volumetric Heat generation, W/m3 ). This heat generation is given to the computational model in the simulations. To dissipate this heat generated a DC fan is enclosed either at the outlet/inlet which supplies air at a constant velocity, which is provided at the inlet of the domain. The lateral boundary condition of the domain is considered as adiabatic cause the heat does not flow through the lateral boundaries.

**Table 2**
Boundary condition

| Locations | Natural convection | Forced convection | Forced convection |
|---|---|---|---|
| Inlet , x=0 | U=0.01 m/s<br>T=T∞ =25 °C<br>$\frac{\partial T}{\partial y}=\frac{\partial T}{\partial Z}=0$ | U=3m/s<br>T=T∞ =25 °C<br>$\frac{\partial T}{\partial y}=\frac{\partial T}{\partial Z}=0$ | U=5 m/s<br>T=T∞ =25 °C<br>$\frac{\partial T}{\partial y}=\frac{\partial T}{\partial Z}=0$ |
| Outlet, x=L | p = p∞ , Lateral Boundary conditions are adiabatic | | |

## 4. Mesh Independency Study

It plays a pivotal role in determining the accuracy and precision of outcomes. In this investigation, all components adopt quad-shaped elements, thus emphasizing the significance of hex-dominant mesh elements for ensuring high-quality results with reliability. To maintain accuracy, the skewness of mesh elements is restricted to below 0.90. Additionally, a mesh independence analysis was conducted to assess result variance with different mesh configurations, as depicted in Fig. 4. It was observed that the maximum temperature of the IC chip stabilized upon reaching 1,616,875 mesh elements. This suggests that further increasing the number of elements does not impact results significantly but aids in reducing computational time. Figures 2 and 3 illustrate the mesh profile employed in this study. A mesh independence study is crucial in Computational Fluid Dynamics simulations to ensure the accuracy and reliability of the results.

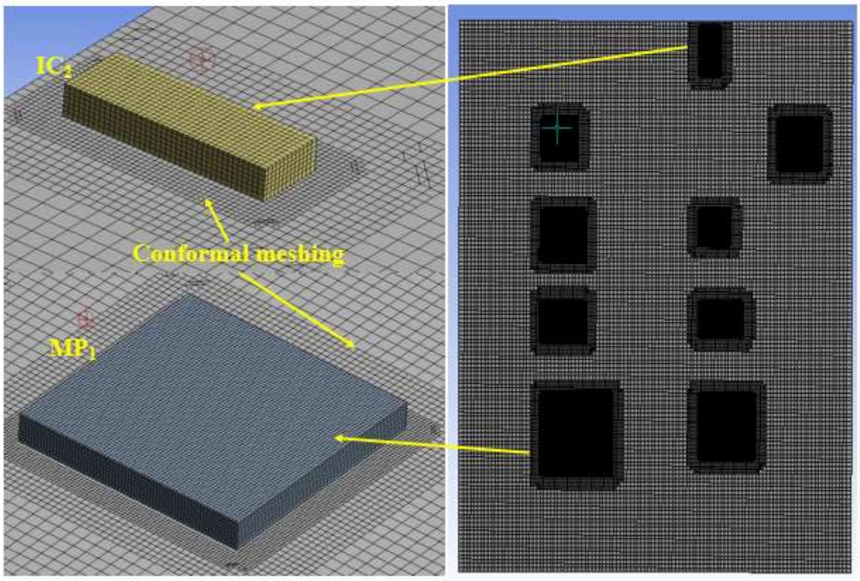



**Fig. 2.** Mesh Profile

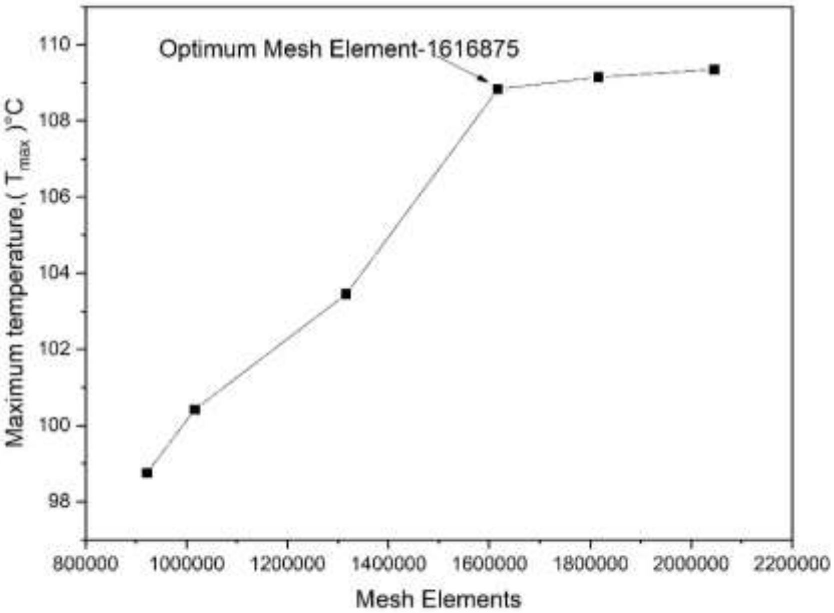



**Fig. 3.** Independency study carried out

## 5. Result and Discussion

This study explained the numerical analysis of electronic components under various heat transfer modes. The components are subjected to varying heat flux and are placed on FR-4, Cu cladding, and Si cladding boards. The aim is to examine how these different modes of heat transfer and substrate materials affect the temperature of electronic components. The findings provide valuable insights for the heat transfer community such as electronic thermal designers in selecting suitable substrate boards for effective thermal management of electronic components. Higher exit temperatures compared to the inlet indicate efficient heat removal from components. Airflow characteristics, such as velocity and uniformity, are crucial—high velocity suggests good cooling but can be noisy and energy-intensive, while uneven flow creates hotspots. Substrate material also affects performance, with copper cladding promoting a more stable temperature profile. Monitoring these factors at the exit helps assess cooling strategies, with forced convection typically being more efficient at higher velocities. Lower exit temperatures with reduced air velocity indicate a more energy-efficient system, and managing exit air temperature is essential to prevent overheating the surrounding environment. The asymmetric IC chips are supplied with high heat flux for the maximum operating condition fetched from the data sheet provided by the manufacturer.

### *5.1 Electronic Components Temperatures*

Figure 4 illustrates the temperature of electronic components under NC and FC at 4 m/s and 6 m/s. Under natural convection, the temperature rises above the critical threshold of 125$^0$C due to the non-uniform heat flux [32]. Increasing the air velocity reduces the temperature of the heat sources, with the lowest temperatures observed at 6 m/s. Among the components, the MP1 has the highest temperature in all scenarios, followed by the MP2 and IC1. The substrate board (FR-4) exhibits lower temperatures due to its lower thermal conductivity. The heat from the IC chips is transferred solely through convection. Figure 6 shows the heat distribution among the heat sources under forced convection, highlighting the thermal interactions between the nine electronic components. Additionally, using a Cu cladding board significantly reduces the air velocity required for cooling by 2 m/s and lowers the IC chip temperature by 3.50$^0$C to 13.12$^0$C.

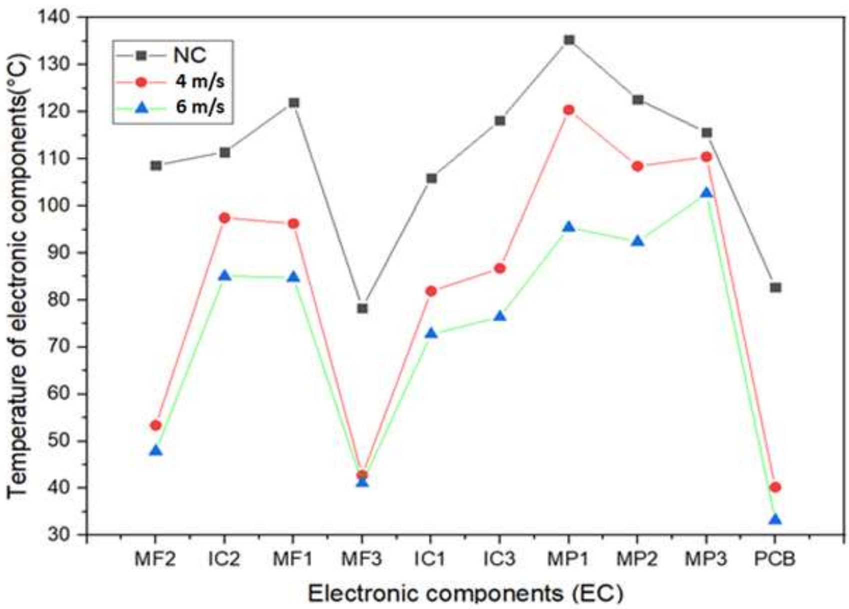
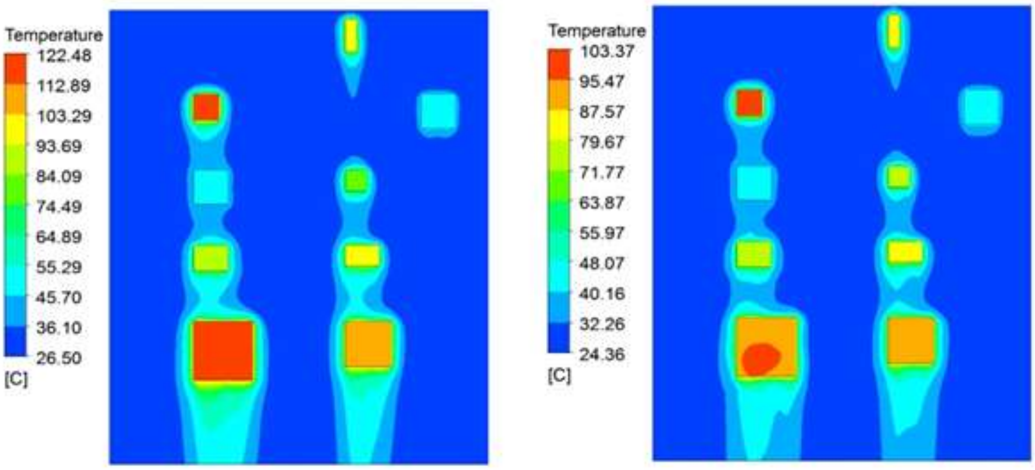



**Fig. 4.** Temperature (NC, 4m/s, 6m/s)




a) b)

**Fig. 5.** Temperature at different substrate board; a) 4 m/s and b) 6 m/s

The temperature of EC's is further lowered by using different substrate materials, specifically FR-4, Cu cladding, and Si cladding. The copper and Si cladding, each 0.7mm thick, are layered above the FR-4 substrate board, making the total thickness 1.75mm. It is observed that the temperature of the electronic components decreases by $34^0$C to $54^0$C when using the cladded substrate materials, as depicted in Fig. 5. Moreover, the temperature of the electronic components is $4^0$C to $12^0$C lower with the copper cladding compared to the Si cladding substrate board, indicating that heat is conducted along the substrate length and convected to the fluid.

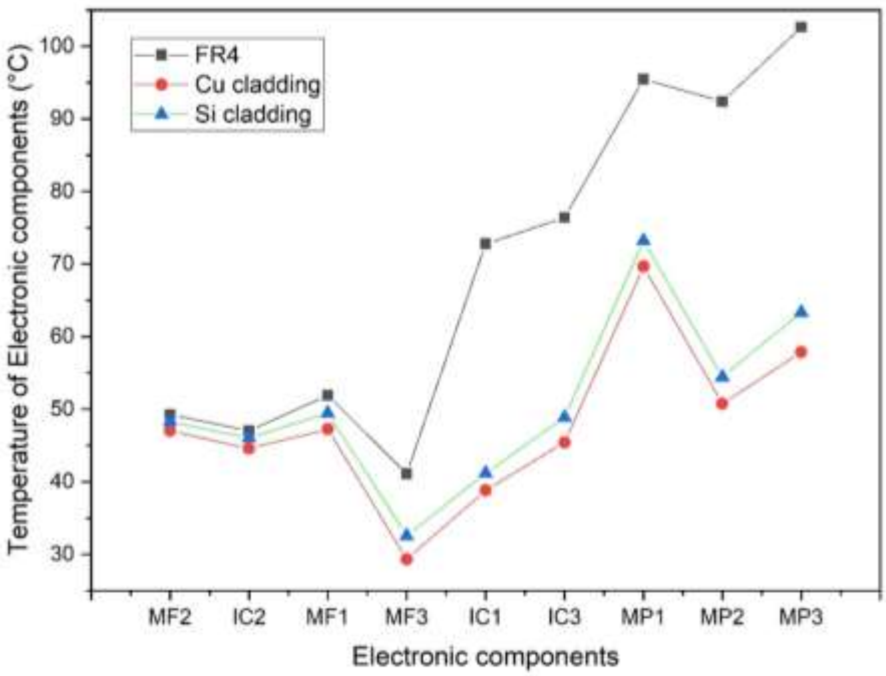



**Fig. 6.** Temperature under 6m/s

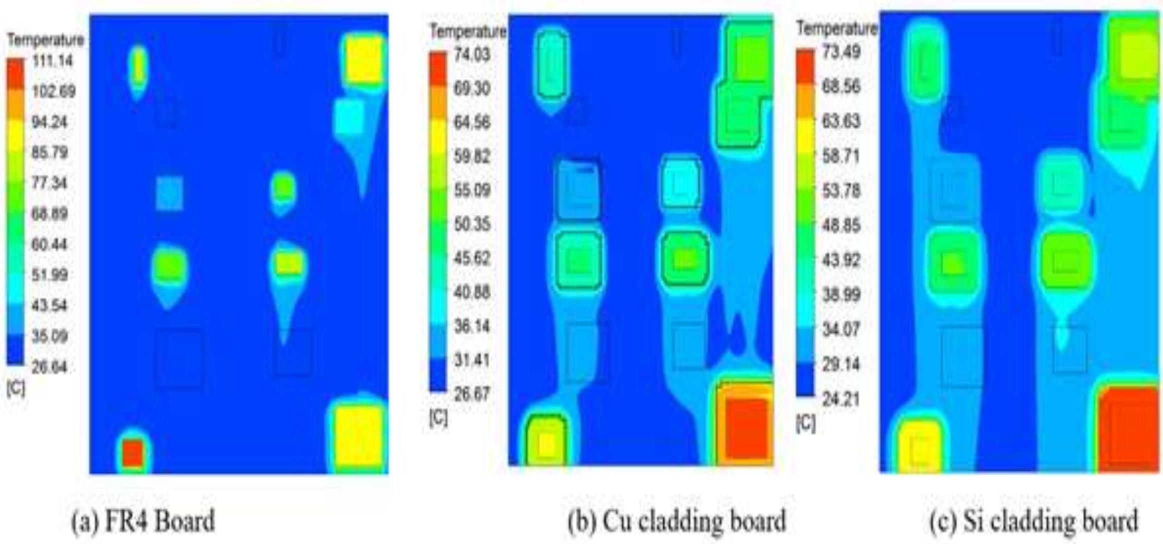



**Fig. 7.** Temperature Contours for Copper, Si, and FR-4 Board

## 6. Conclusion

This study investigated the impact of heat transfer modes and substrate materials on electronic component temperatures using numerical analysis. The key findings are,

i) Copper cladding significantly reduces component temperatures (34-54°C) compared to FR-4 and Si boards at an air velocity of 6 m/s.
ii) Copper cladding allows lower air velocity requirements (2 m/s reduction) for achieving the same cooling effect.
iii) Copper cladding leads to lower IC chip temperatures (3.5-13.12°C) for improved reliability.
iv) Utilizing copper cladding with an air velocity of 4 m/s maintains temperatures below 125°C, minimizing fan power consumption.
v) Copper cladding is a superior choice for efficient thermal control of electronic components.
vi) It is recommended to use an air velocity of 4m/s with copper cladding to minimize fan power consumption while maintaining component temperatures below 125°C.
vii) Strategic placement of high heat-dissipating components can minimize thermal interaction and improve overall configuration temperature.

This research provides valuable knowledge for the heat transfer community and electronic thermal designers, aiding in the development of reliable and long-lasting electronic systems.

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