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Impact of PCM on Heat Dissipation from IC Chips

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Abstract

This study systematically investigates the thermal performance of nine Integrated Circuits (ICs) arranged in symmetric and asymmetric configurations on a substrate board. The analysis considers two scenarios: with and without the incorporation of Phase Change Material (PCM). The ICs were subjected to varying heat flux levels to assess their thermal behavior under different operating conditions. Results indicate that the temperature of the ICs is significantly influenced by factors such as IC size, positional arrangement, and the magnitude of the applied heat flux. The study also examines the role of the non-dimensional geometric distance parameter (λ), which varies with both IC size and location on the substrate. At a specific λ value of 0.19, notable temperature reductions were observed. Without PCM, temperature reductions of 18.79% and 26.48% were recorded at airflow velocities of 3 m/s and 5 m/s, respectively. The integration of PCM led to further enhancements, achieving reductions of 23.58% at 3 m/s and 32.47% at 5 m/s. These findings underscore the effectiveness of PCM in improving thermal management by efficiently absorbing and dissipating heat. Further statistical analysis revealed a strong correlation between the non-dimensional temperature parameter (θ) and λ, with a coefficient of determination (R^2) of 0.97 and a Root Mean Square (RMS) error of 0.012%. Higher λ values consistently correlated with lower peak IC temperatures, suggesting that increasing the spatial separation between heat-generating components enhances heat dissipation and overall thermal performance. These

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findings have critical implications for thermal design engineering. By strategically optimizing IC placement on substrates, engineers can improve the reliability and lifespan of electronic systems. Additionally, the integration of PCM offers a practical solution for managing heat in compact electronic assemblies, providing a foundational framework for advanced cooling strategies in modern electronic devices.

Major Findings: *Temperature Dependence: The temperature of an IC is significantly influenced by its size, location on the board, and the amount of heat it generates. The non-dimensional geometric distance parameter (λ) also plays a crucial role in determining temperature distribution. Impact of PCM: The integration of PCM resulted in a substantial temperature reduction, ranging from 18.79% to 32.47%, compared to configurations without PCM, especially for higher λ values (0.19). Improved Chip Lifespan: By lowering IC temperatures through PCM-based cooling, the lifespan of the chips can be significantly extended, as they operate within optimal temperature ranges.*

Keywords: IC Chips, Phase Change Material, SMPS Board, Thermal Management

1.0 Introduction

The rapid growth of the electronics industry and the drive for smaller components has led to increased heat generation, posing challenges to reliability. Effective thermal management is crucial for optimal performance and durability of devices, preventing failures caused by high operating temperatures. This research focuses on evaluating the effectiveness of heat sinks in dissipating heat from ICs, aiming to optimize thermal management and improve overall performance. Previous studies have explored various aspects of thermal management. Ramadhyani *et al.* investigated the impact of substrate thermal conductivity on heat transfer from buried heat sources[1]. Faghri *et al.* studied turbulent flow and heat transfer in rectangular blocks[2]. Culham *et al.* used numerical modelling to predict local chip temperatures[3]. Chen and Liu optimized forced convection arrangements for multiple heat sources[4]. Chuang *et al.* numerically simulated heat transfer in different configurations[5]. Furukawa and Yang explored the effect of board thickness on heat transfer[6]. Yadav and Kant studied heat transfer from heated modules, considering array size and substrate temperature[7]. Baudoin *et al.* optimized passive cooling arrangements for heat sources[8,9]. Durgam *et al.* optimized rectangular heat sources on PCB[10]. They investigate the application of PCM for cooling high-power electronic components, particularly smartphones. Traditional cooling methods, including natural convection, heat pipes, and forced convection, often fail to meet the demands of high-power systems. To address this, the proposed design incorporates PCMs into mini channels surrounding the IC chips. As the IC components heat up, the PCM absorbs the thermal energy and undergoes a phase change, effectively managing the heat dissipation. Among the tested PCMs, N-Eicosane exhibited superior cooling performance, achieving significant temperature reductions compared to other PCMs and systems without PCM. This innovative approach offers a practical solution for enhancing the thermal management of high-power electronic devices[11–15]. They introduce a novel faucet design aimed at addressing hygiene and water conservation challenges in developing countries. By analyzing existing literature, the authors identified a critical need for such a device. A prototype was developed to meet these specific requirements, providing a practical solution to these issues[16]. The paper reviews the machining challenges of Hybrid Metal Matrix Composites (HMMCs), which are known for their superior mechanical properties and lightweight characteristics, making them ideal for the automotive and aerospace industries. The study focuses on optimizing machining parameters, including cutting forces, Material Removal Rate (MRR), tool life, and surface finish. It highlights the effects of reinforcement properties and cutting conditions on machinability, offering strategies to improve performance during machining[17]. Advancements in thermal management are crucial for various industries. Techniques like mini jet impingement enhance heat transfer in tubular heat exchangers by directing high-velocity fluid jets onto the heat transfer surface. Twisted tape inserts with circular holes further augment heat transfer efficiency in forced convection systems. In the realm of renewable energy, optimizing biodiesel-dimethyl carbonate blends improves the performance of diesel engines. Nanofluids, engineered fluids containing nanoparticles, significantly enhance

thermal conductivity in heat exchangers. Additionally, optimizing aerofoil design through CFD simulations and wind tunnel experiments leads to improved aerodynamic efficiency, benefiting applications like aircraft and wind turbines[18–28]. Further research avenues explore optimizing heat transfer across various applications. Innovative tape inserts can enhance heat exchanger designs while analyzing wind patterns and optimizing sensor placement can improve wind turbine performance. Integrating PCM and carefully selecting substrate materials can increase the thermal efficiency of electronic components. These multidisciplinary approaches collectively aim to advance heat transfer techniques and improve performance in electronic devices, renewable energy systems, and industrial heat exchangers[29–35].

Previous research predominantly focused on symmetric IC chips with a uniform heat flux distribution, limiting the scope of thermal management insights for more complex configurations. This study seeks to address this gap by investigating the thermal behavior of both symmetric and asymmetric IC chips under varying heat flux conditions. The primary objective is to identify the optimal chip arrangement that minimizes the maximum temperature across the IC components, ensuring enhanced thermal performance.

Additionally, the research explores the integration of PCMs as an advanced cooling solution. PCMs absorb and dissipate heat through phase transitions, offering the potential to significantly enhance temperature regulation. By combining analysis of chip configurations with the use of PCM, this study aims to provide a comprehensive understanding of the factors influencing thermal performance.

1.1 Key Objectives

1. Evaluating the impact of chip symmetry and arrangement on heat dissipation efficiency.
2. Quantifying temperature reductions achieved through PCM integration in both symmetric and asymmetric setups.
3. Identifying the configuration that achieves the lowest peak temperatures, thus enhancing the reliability and longevity of electronic components.
4. Providing actionable insights for engineers and designers to optimize IC placement and cooling mechanisms for high-performance applications.

The findings are expected to contribute to the development of innovative thermal management strategies, addressing the challenges posed by increasing power densities and shrinking component sizes in modern electronic systems.

2.0 Design of Circuit Board and IC Chips on an SMPS Board Incorporating PCM

A comprehensive total of 170,554 distinct configurations can be achieved for arranging nine rectangular heat sources, encompassing both symmetric and asymmetric geometries, on a Printed Circuit Board (PCB). The PCB substrate, with dimensions of 269 mm × 189 mm × 5 mm, is fabricated using copper cladding, which provides excellent thermal conductivity and electrical properties, making it suitable for heat dissipation applications. Each unique arrangement of the heat sources is characterized by

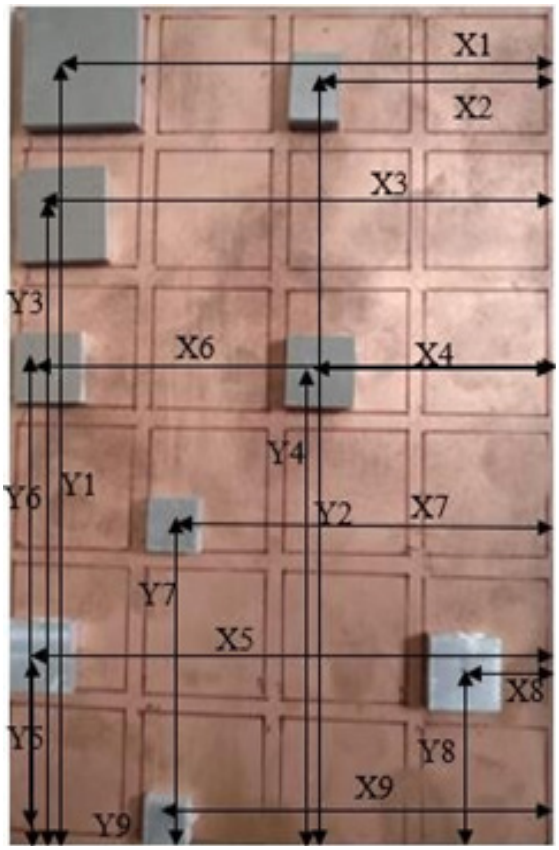


Figure 1. Positions of IC chips.

a specific non-dimensional geometric distance parameter, **λ**, which varies from 0.28 to 1.9. This parameter plays a crucial role in determining the spatial configuration and thermal interactions of the heat sources on the PCB. To efficiently generate and catalogue these arrangements along with their corresponding λ values, a MATLAB script was developed. This tool enabled systematic exploration of the vast design space, ensuring precise calculation of the λ values for all possible configurations. For in-depth numerical analysis, a subset of 30 diverse configurations was selected randomly from the full range of λ values between 0.28 and 1.9. These selected arrangements represent a broad spectrum of spatial layouts, allowing for a detailed investigation into the impact of heat source positioning on thermal performance. This methodological approach not only provides a foundation for understanding heat dissipation behaviour but also aids in identifying optimal configurations for improved thermal management in electronic systems.

30 distinct configurations of nine rectangular heat sources on a PCB, each characterized by a unique non-dimensional geometric distance parameter (λ). This parameter quantifies the spacing between heat sources, with lower values indicating closer proximity and higher values representing greater separation. The configurations range from symmetric to asymmetric arrangements, allowing for a comprehensive analysis of thermal behaviour. By studying these configurations, researchers can identify the optimal heat source layout that minimizes peak temperatures and maximizes heat dissipation efficiency on the PCB.

Ceramic brackets were fabricated to support the ICs on a substrate board, with their exact locations determined by X and Y coordinates as shown in Figure 1. These brackets were designed to hold IC chips and were filled with Paraffin wax, a PCM with a melting point between 48.28°C and 54.21°C, ideal for heat absorption. The wax, initially in solid form, was pulverized and inserted into mini channels within the brackets to maximize heat absorption. Thermocouples were embedded in the brackets and PCM to monitor temperatures. Aluminium chips, representing ICs due to their high thermal conductivity, were used in simulations to ensure accurate heat transfer analysis. The mini-channel design facilitates direct heat absorption from the heat source, while Paraffin wax, chosen for its favourable thermal properties, enhances heat storage and dissipation detailed in Table 1. This innovative approach effectively manages thermal loads, ensuring optimal performance and longevity of electronic systems.

Table 1. Thermophysical characteristics of paraffin wax

Sl. No.	Property	Value
1	Density (kg/m^3)	800-900
2	Specific Heat Capacity (J/kg·K)	2000-3000
3	Thermal Conductivity (W/m·K)	0.15-0.30
4	Latent Heat of Fusion (J/kg)	150,000-250,000
5	Melting Point Range (°C)	48

3.0 Experiment Set Up and Procedure

To assess the thermal performance of 30 different IC chip configurations, steady-state experiments were conducted under forced convection conditions in a wind tunnel. The experimental setup adhered to JEDEC Standard No. 51-6, ensuring reliable and consistent results. Initial simulations under natural convection indicated that the IC chips would exceed safe temperature limits. To address this, experiments were conducted at airflow velocities of 3 m/s and 5 m/s. These velocities effectively reduced chip temperatures, ensuring safe operation. The experiments were performed under ambient conditions between 25°C and 30°C, with the initial chip temperature assumed to be equal to the ambient temperature. A gentle airflow was directed towards the chips to regulate temperature. The heat flux applied to the chips corresponds to their maximum rated power dissipation. The primary objective was to determine the optimal airflow velocity for efficient cooling. The results demonstrated that both 3 m/s and 5 m/s velocities effectively maintained chip temperatures within safe limits under high heat flux conditions. This highlights the importance of airflow management in thermal design, particularly for high-performance electronic systems.

3.1 Experimental Procedure for Steady-State Laminar Forced Convection

The wind tunnel was initially set up to maintain a consistent and uniform air velocity throughout the test section, employing axial airflow to achieve controlled conditions. This configuration ensured that the temperature around the substrate board and the IC chips remained stable and close to the ambient temperature, approximately 30°C. Such stability was crucial for accurately evaluating the thermal performance of the system. The experiment began by activating the DC power source, which supplied the required heat input to the IC chips. The voltage and current levels were meticulously adjusted to achieve the desired heat flux. This precise control ensured that the heat generation closely simulated real-world operating conditions for the IC chips. A temperature data logger, interfaced with a computer via a Serial Communication Port, continuously monitored and recorded the temperature readings from multiple thermocouples. The thermocouples were strategically positioned to capture detailed thermal data. To accurately assess the thermal performance of the system, temperature measurements were taken at critical locations. Thermocouples were strategically placed to monitor the temperatures of the IC chips, the mini-channels, and the Phase Change Material (PCM). This data provided valuable insights into heat generation, dissipation, and storage within the system. The data logger collected and transmitted temperature readings in real-time to a computer system, enabling continuous monitoring of the thermal performance. The recorded data were analyzed and visualized using specialized software, as depicted in Figure 2, providing a comprehensive view of the heat transfer process. The experimental setup incorporated several key features to ensure accurate and reliable results. An axial flow design provided consistent cooling across all components, eliminating air flow variations. Real-time data logging allowed for precise monitoring of temperature changes and system behavior under different heat loads. Additionally, precise control over voltage and current levels enabled accurate heat flux application to the IC chips, ensuring repeatable experimental conditions. The setup enabled a detailed assessment of the thermal management system, including the effectiveness of the mini-channel design and the performance of the PCM in mitigating heat. By maintaining stable ambient conditions and capturing high-resolution temperature data, the experiment provided valuable insights into optimizing the thermal performance of electronic systems.

4.0 Results and Discussion

To assess the thermal performance of different substrate board configurations, steady-state experiments were conducted both with and without Phase Change Material (PCM). The study focused on the impact of the non-dimensional geometric distance parameter (λ) on temperature reduction. Higher λ values, such as 0.19, resulted in significant temperature decreases. Without PCM, temperature reductions of 18.79% and 26.48%

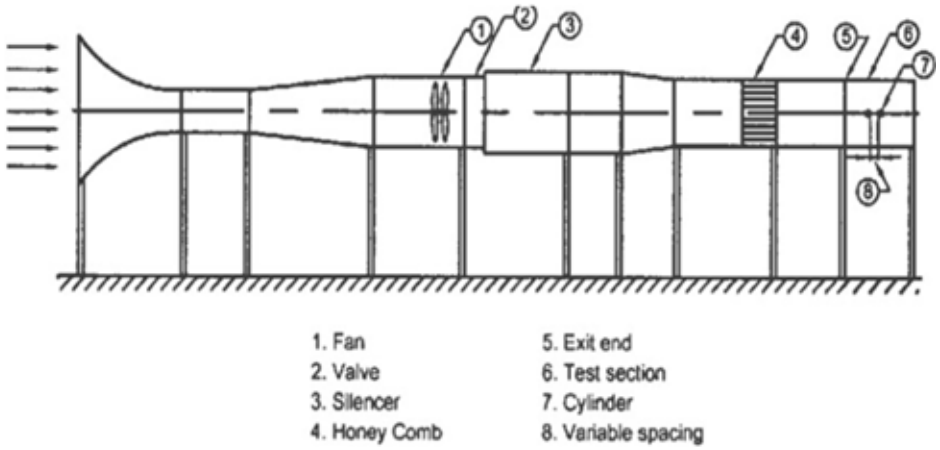


Figure 2. Experimental setup.

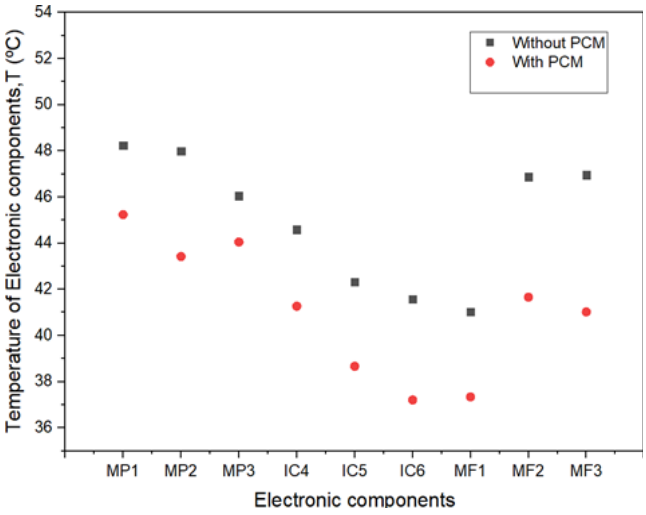


Figure 3. At 3 m/s for a higher λvalue of 1.9

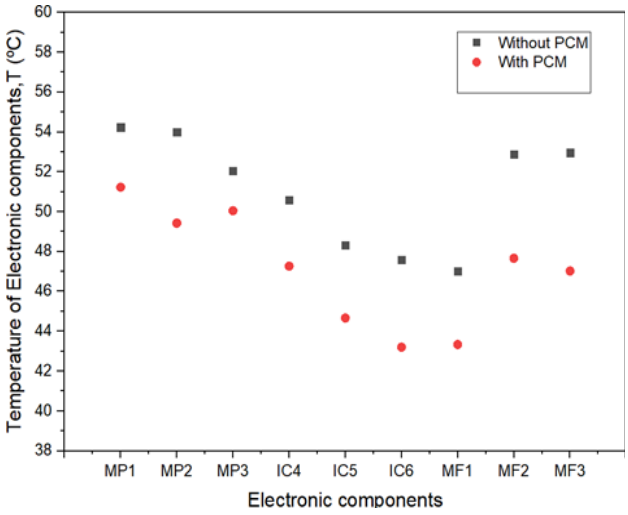


Figure 5. At 3 m/s for higher λ 0.28

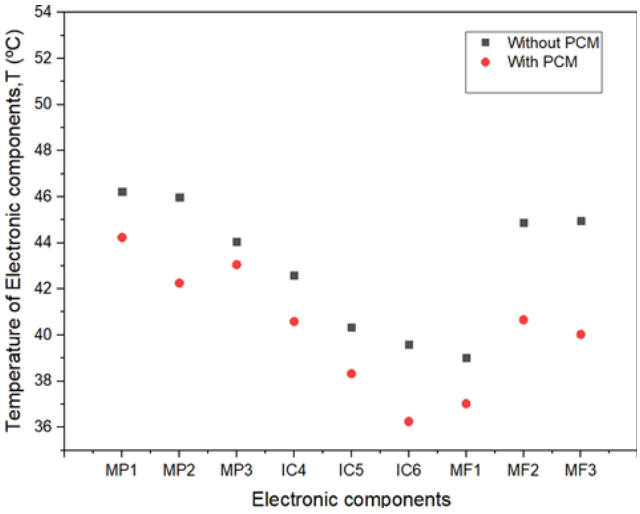


Figure 4. At 5 m/s for a higher λ value of 1.9.

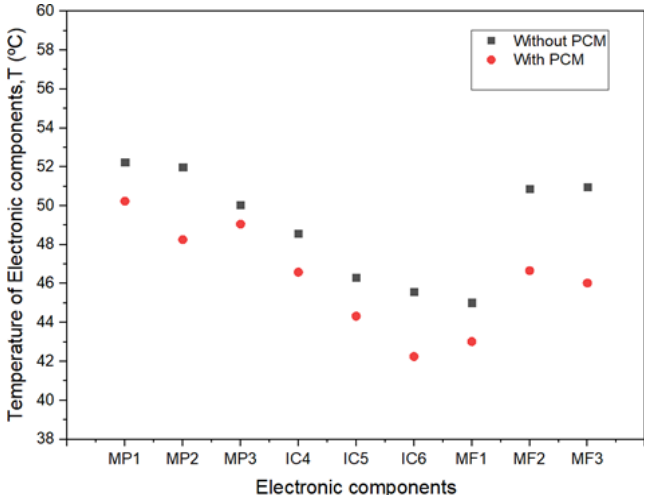


Figure 6. At 5 m/s for higher λ 0.28.

were observed at airflow velocities of 3 m/s and 5 m/s, respectively. With PCM, these reductions increased to 23.58% and 32.47%, respectively as shown in figure 3,4,5,6. The integration of PCM proved highly effective in reducing peak temperatures. PCM absorbs heat during phase change, storing thermal energy and stabilizing chip temperatures. This effect is particularly noticeable at higher airflow velocities, where the combined effect of forced convection and PCM enhances cooling efficiency. Higher λ values, which correspond to greater spacing between heat sources, enhance airflow and heat dissipation. The combination of increased airflow velocity and the use of Phase Change Material (PCM) significantly amplifies temperature reduction. This study offers valuable insights for optimizing thermal management strategies in high-performance electronic systems.

Reducing the airspeed to 3 m/s led to a temperature increase of 3.15 to 11.12 °C in the electronic components. However, this reduction in airspeed significantly lowered fan power consumption while still maintaining component temperatures within safe limits.

5.0 Conclusion

This research focused on reducing the temperature of ICs using mini-channels filled with Phase Change Material

(PCM) under mixed convection conditions. Steady-state experiments were conducted on a substrate board with nine ICs arranged in various configurations and subjected to different heat fluxes.

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