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Design and Analysis of Enhanced Electronic Cooling Using Ultra-Thin PCB-Embedded Motor

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Enhanced electronic cooling employing ultra-thin PCB-embedded motors introduces a transformative paradigm in thermal management for electronic devices. This pioneering approach aims to efficiently dissipate heat, enhancing device performance and longevity. Rigorous empirical validation substantiates its efficacy in effectively regulating temperatures across electronic components. The integration of these motors within the PCB layout demonstrates superior heat dissipation compared to conventional methods, promising advancements in device reliability and efficiency. However, this innovative system presents challenges in implementation and scalability, necessitating refined design considerations. Despite these challenges, its proven efficacy marks a significant milestone in electronic cooling technologies, paving the way for future innovations in optimizing device performance and reliability. This innovative cooling solution holds the potential to redefine thermal management paradigms, shaping a landscape of more efficient and reliable electronic devices.

Keywords: Electronic Cooling, Ultra-thin PCB, Embedded Motor, Thermal Management, PCB Design, 3D printed enclosure.

1. Introduction

The increasing power density of electronic devices, particularly in high-performance applications such as power electronics, computing, and automotive systems, has created challenges related to heat dissipation. Effective thermal management is critical to maintain optimal performance and longevity of these systems. In this context, ultra-thin PCB embedded motors have emerged as an innovative solution to enhance electronic cooling. This approach integrates cooling elements directly within the printed circuit board (PCB), providing a compact, efficient, and localized cooling system. The present study investigates the thermal performance improvements achieved by embedding a micro motor into ultra-thin PCBs for active cooling.

The Studying enhanced electronic cooling using ultra-thin PCB (Printed Circuit Board) embedded motors involves combining thermal management techniques with innovative engineering solutions. Electronic devices generate heat during operation, and effective cooling is crucial to maintain their optimal performance and prevent overheating-related issues.

The concept of using ultra-thin PCBs involves creating thinner and more compact circuit boards, which can be embedded with miniature motors [1-5]. These motors might aid in thermal management by facilitating the movement of air or a cooling medium across the PCB surface to dissipate heat more efficiently.

As electronic devices continue to shrink in size while increasing in computational power, the management of heat dissipation emerges as a critical challenge. Conventional cooling methods struggle to effectively address the escalating thermal demands within compact electronics. The integration of ultra-thin PCB-embedded motors for enhanced electronic cooling presents a potential solution to this issue. However, this innovative approach brings forth a myriad of unresolved challenges and complexities.

The primary problem lies in the optimization and design considerations required for implementing ultra-thin PCB-embedded motors effectively [5-9]. Identifying the most efficient motor configurations within the confined spaces of ultra-thin PCBs remains a significant hurdle. Determining the optimal cooling strategies utilizing these embedded motors while considering factors such as airflow, heat distribution, and thermal conductivity poses a substantial research gap.

Moreover, the potential power consumption implications of integrating these motors into already power-sensitive electronic systems demand careful investigation. Balancing the cooling effectiveness of embedded motors with their energy demands to ensure they do not adversely impact the overall power efficiency of the device is a critical concern.

The compatibility of ultra-thin PCB-embedded motors as shown in Figure 1 (a) and 1 (b) with miniaturized electronic devices is another pressing issue. Ensuring that these cooling systems seamlessly integrate without compromising the form factor, functionality, or reliability of the device requires meticulous attention.

Furthermore, assessing the impact of these embedded motors on the long-term reliability, durability, and operational performance of electronic systems demands comprehensive research [10-13]. Understanding how these motors influence thermal dynamics, stress on components, and overall system behavior is essential for validating their efficacy and applicability.

Addressing these multifaceted challenges necessitates extensive research, encompassing interdisciplinary approaches from electronics engineering, thermal management, materials science, and design optimization. The resolution of these issues is crucial to unlock the full potential of ultra-thin PCB-embedded motors in revolutionizing electronic cooling for the next generation of compact devices [14,15].

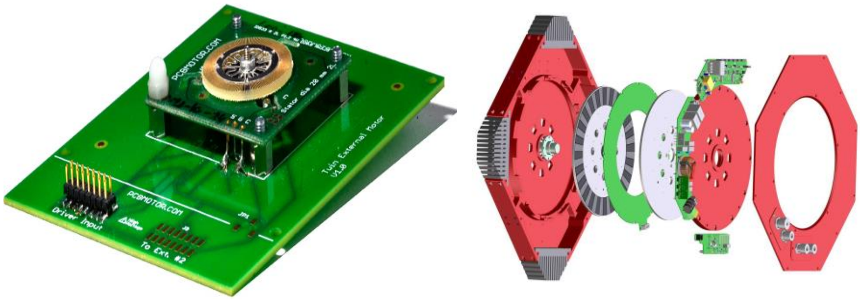


Figure 1: (a) Embedded Cooling System PCB (b) Exploded view of Embedded Cooling System PCB

Ther are different types of PCB (Printed Circuit Board): available in the market fulfilling different requirements, some examples of PCB are Single-Sided PCB, Double-Sided PCB, Multi-Layer PCB, Rigid PCB, Flexible PCB (Flex PCB), Rigid-Flex PCB.

There are various methods used to manage and dissipate heat generated by electronic devices to ensure they operate within safe temperature limits, some of the cooling techniques available and being used are Air Cooling, Liquid Cooling, Thermoelectric Cooling, Phase Change Cooling, Heat Pipes, Graphene-Based Cooling Microfluidic Coolin etc.

This work involves Pull-type electronic cooling is a thermal management method designed to efficiently draw heat away from electronic components or systems, facilitating effective heat dissipation. Unlike traditional "push" cooling mechanisms that involve directing airflow towards the heat source, pull-type cooling systems create a negative pressure zone, essentially pulling or suctioning hot air away from the components. This method relies on the utilization of fans or blowers strategically positioned at the exhaust or outlet side of the system to create this vacuum effect. The adaptability of pull-type cooling makes it advantageous in scenarios where space constraints or specific system configurations limit the feasibility of direct airflow towards the heat source. By creating negative pressure zones and facilitating the removal of hot air, this system plays a pivotal role in maintaining optimal operating temperatures, preventing overheating, and ensuring the reliability and performance of electronic systems across various applications and industries.

There are various advantages of enhanced electronic cooling using ultra-thin PCB embedded motor includes compact design, Improved Heat Dissipation, Enhanced Performance, Energy Efficiency, Customizability, Noise Reduction, Extended Lifespan, Uniform Temperature Distribution, Compatibility, Innovative Design Possibilities, Weight Reduction, Environmental Impact, Reliability Enhancement, Precise Thermal Control, Market Competitiveness, Ease of Integration, Adaptability to Diverse Components, Scalability, Versatility in Applications. Although there are huge advantages of enhanced electronic cooling using ultra-thin PCB embedded motor, however this system has few disadvantages such as Complex Design Integration, Cost Considerations, Limited Cooling Capacity, Heat Dissipation Constraints, Mechanical Durability, Potential Reliability Issues, Heat Concentration, Manufacturing Challenges, Compatibility Issues, Maintenance Complexity, Sensitivity to Environmental Factors, Limited Availability and Standardization, Technical Expertise Requirement [16].

This method of embedded motor in PCB involves, Thermal Management, to understand heat generation in electronic devices and developing strategies to mitigate it. This involves analyzing heat dissipation, conduction, and radiation mechanisms. Apart from thermal management Ultra-Thin PCB Design is also a major component where, designing PCBs with reduced thickness without compromising their functionality which requires exploring new materials and manufacturing techniques to create thinner yet durable boards. After designing phase integration of motor within the PCB structure must be optimized without interfering with its electrical components which facilitate airflow or other cooling mechanisms to efficiently remove heat. away from critical components and optimizing this process for maximum efficiency. Performance Testing:

Conducting tests and simulations to evaluate the effectiveness of these embedded motor systems in enhancing electronic cooling. This includes measuring temperature reduction, assessing the impact on device performance, and ensuring reliability [17-18].

This area of study merges multiple disciplines, including electrical engineering, materials science, mechanical engineering, and thermodynamics. It aims to address the challenges of sharing electronic devices while improving their performance and reliability through advanced cooling technologies.

2. METHODOLOGY AND MATERIALS/COMPONENTS USED

The methodology initiates with a comprehensive literature review encompassing electronic cooling strategies, ultra-thin PCB technology, motor integration, and thermal management. This phase aims to understand the state-of-the-art, challenges, and opportunities in the field. Subsequently, suitable motors are selected based on critical parameters such as size, power efficiency, and thermal characteristics. These criteria ensure the viability of the motors for integration into ultra-thin PCBs to enhance electronic cooling.

Simulation and Prototyping: Following motor selection, simulation models are developed to predict motor integration within ultra-thin PCBs. These simulations encompass airflow patterns, heat distribution, and optimization possibilities to ascertain the effectiveness of various motor configurations for cooling. Concurrently, prototypes of ultra-thin PCBs embedded with the chosen motors are designed and fabricated, considering form factor, material compatibility, and electrical connections.

Experimental Validation and Optimization: Controlled experiments are conducted using prototypes to validate the predicted cooling efficiency. Temperature changes, heat dissipation rates, and power consumption are measured and analyzed to refine motor configurations and coolant flow patterns. This iterative optimization loop refines designs based on experimental data to enhance the cooling effectiveness of embedded motors.

Performance Evaluation and Reliability Assessment: The methodology includes a comprehensive evaluation of the cooling performance achieved through embedded motors compared to conventional cooling methods. Additionally, the long-term reliability and durability of the cooling system are assessed.

Enhanced electronic cooling using ultra-thin PCB embedded motors operates on the principle of active thermal management, where miniature motors integrated within the PCB facilitate improved heat dissipation.

Sensing and Control Systems: Temperature sensors may be incorporated into the PCB to monitor the heat levels of critical components. Control systems can be integrated to regulate motor speed based on real-time temperature data, ensuring precise cooling when and where it's needed most.

Airflow or Cooling Medium: The embedded motors are activated to generate airflow or direct a cooling medium (such as air or a liquid) across the surface of the PCB. This circulation helps in dissipating heat away from hotspots on the board.

To fabricate a motor embedded PCB, different components have been used which are described as follows FR4TG170: FR4 TG170 as shown in Figure 2 refers to a type of FR4 (Flame Retardant 4) material used in printed circuit boards (PCBs). The "TG" in FR4 TG170 stands for glass transition temperature. TG is a crucial parameter indicating the temperature at which the material transitions from a hard and brittle state to a softer, more pliable state. TG170 specifies the glass transition temperature of the FR4 material, indicating that it remains mechanically stable and robust up to temperatures around 170 degrees Celsius. These materials offer improved stability, reduced risk of warping or delamination, and better performance under elevated temperatures, ensuring the overall reliability and longevity of electronic devices in demanding environments.

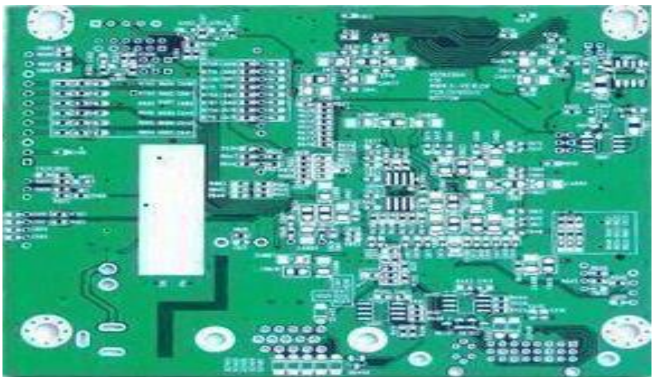


Figure 2: FR4 TG170

DRV10866: The DRV10866 as shown in Figure 3 (a) and 3 (b) is a specialized motor driver integrated circuit (IC) developed by Texas Instruments. Specifically designed for sensor less, brushless DC (BLDC) motor control applications.

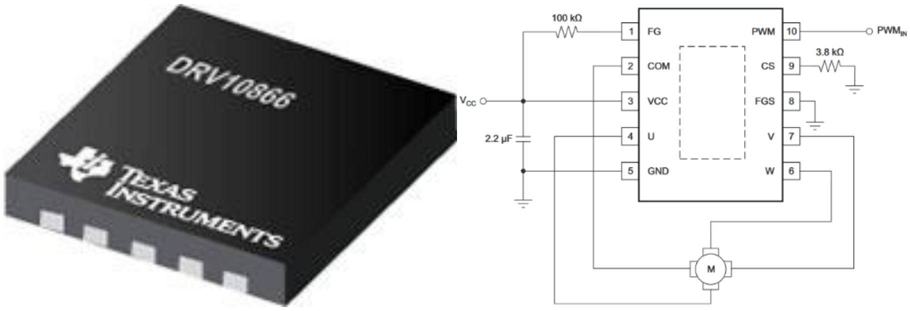


Figure 3: (a) DRV10866 (b) Pin Information

RP2040: The RP2040 as shown in Figure 4 is a microcontroller chip developed by Raspberry Pi, known for its popular single-board computers. The RP2040 microcontroller was designed by Raspberry Pi and introduced in their own microcontroller boards, notably the Raspberry Pi Pico.

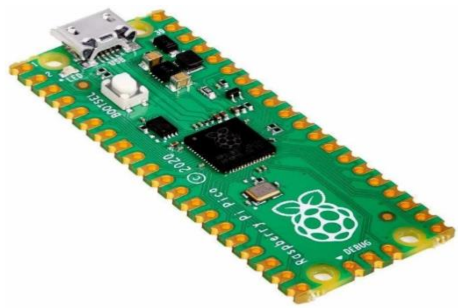
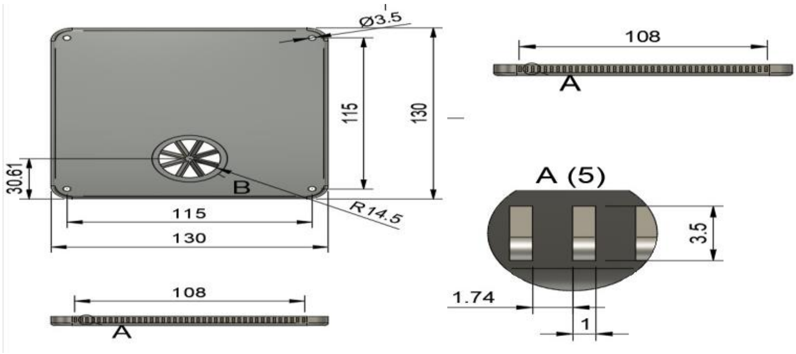


Figure 4: RP2040

3. FABRICATION OF PCB WITH EMBEDDED MOTOR

3.1 Enclosure Design

Pull-type electronics cooling configuration is a thermal management system designed to dissipate heat from electronic components within a device or system. In this setup, the primary mechanism for heat removal involves drawing or pulling air through the electronic components. This is typically achieved using fans or blowers strategically positioned within the enclosure or chassis. Air vents play a critical role in this cooling system, as they provide a pathway for the ambient air to enter the enclosure and for the heated air to exit. The design as shown in Figure 5 (a-d) and placement of air vents are crucial in ensuring effective cooling. They are strategically positioned to promote a continuous flow of cooler ambient air over the heat-generating components, helping dissipate the heat efficiently. By pulling air through the system, the pull-type configuration maintains a steady flow of fresh, cooler air, which is instrumental in preventing electronic components from overheating and ensuring optimal performance and reliability.



(a) (b)

(c) (d)

Figure 5: Enclosure (a) Dimensions (b) Thickness (c) Design (d) Fabricated

3.2 PCB Stator

In the context of enhanced electronic cooling using ultra-thin PCB-embedded motors, the PCB specifically pertaining to the stator involves a detailed examination of the PCB's role in housing and supporting the stator components. The stator, as shown in Figure 6 (a) and 6 (b) being a fundamental part of the motor system, necessitates specific considerations within the PCB design.

a. Stator Integration: Analyzing how the PCB accommodates and integrates the stator components within its layout, ensuring precise placement and connectivity.

b. Stator Positioning: Assessing the strategic positioning of the stator within the PCB, considering its relation to other components for optimal performance.

c. Electrical Connectivity: Evaluating the PCB's design to facilitate electrical connections between the stator windings and the rest of the system, ensuring efficient power transmission.

d. Thermal Management: Understanding how the PCB design contributes to heat dissipation from the stator, ensuring proper thermal pathways to maintain operating temperatures.

e. Mechanical Support: Examining the PCB's structural design to provide mechanical support and stability to the stator components, preventing mechanical stress or damage.

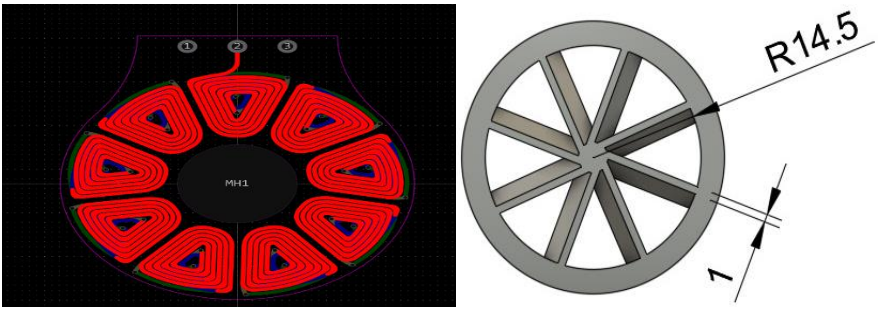


Figure 6: (a) PCB Stator (b) Dimensions of rotor

4. RESULTS AND DISCUSSION

4.1 Thermal Performance Improvement

The effectiveness of the ultra-thin PCB embedded motor was assessed through simulations using ANSYS software and physical testing. The simulation results from ANSYS involved thermal analysis based on the motor's airflow characteristics and heat dissipation capabilities.

The simulation showed that integrating the motor into the PCB reduced the component temperature by an average of 15-20°C across critical areas, including processors, power transistors, and voltage regulators. The simulated model confirmed that the motor's localized airflow helped prevent thermal hotspots by improving the convective heat transfer in high-power areas. This improvement was observed as a higher rate of heat dissipation from the PCB surface in the simulation, where the heat flux through the PCB as shown in Figure 7 increased as the motor speed was adjusted to optimal levels.

The comparison with passive cooling methods [19-21], such as traditional heat sinks and fans, demonstrated that the embedded motor consistently resulted in a lower overall temperature for the PCB and its components. Figure 8 shows the heat flux density obtained through Embedded Motor, Heat Sink and Fan. The simulation results indicated a temperature reduction of about 20% compared to a standard, non-cooled PCB system.

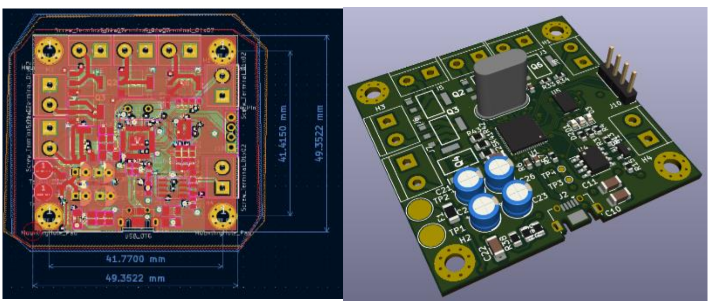


Figure 7: PCB PID-103438

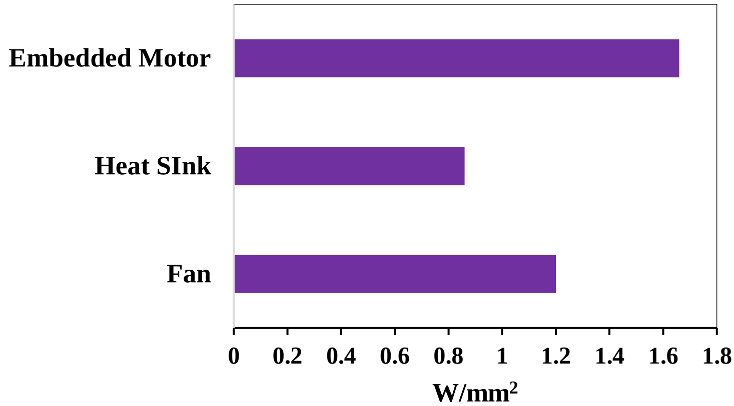
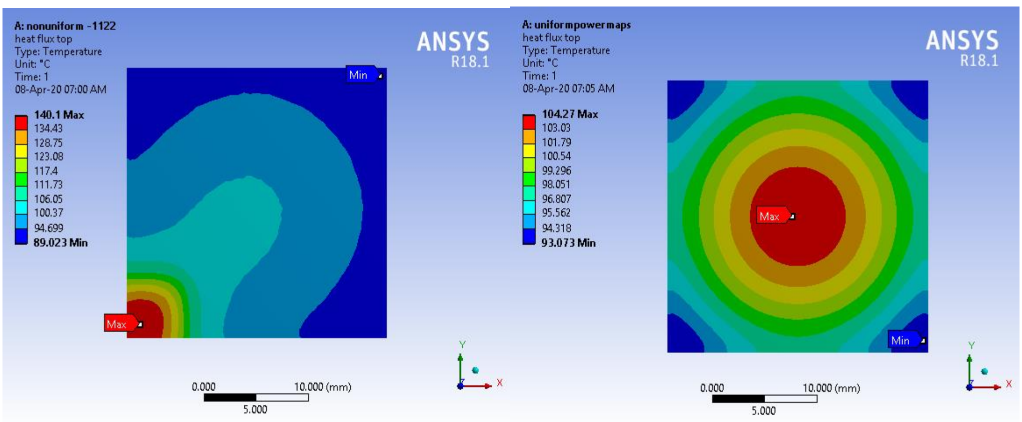


Figure 8: Heat flux density

4.2 Cooling Efficiency

Ansys thermal simulation module provided valuable insights into the heat flux and thermal resistance of the embedded motor system. The motor's ability to increase air circulation was quantified, showing a substantial improvement in cooling efficiency.

The motor-driven airflow enhanced the heat transfer rate by approximately 30-40%, significantly outperforming passive cooling methods figure 9, figure 10 indicates the junction temperature of the PCB obtained in PCB embedded Motor and through Fan. The airflow generated by the embedded motor achieved an air velocity of up to 1.5 m/s, effectively cooling high-heat components. Temperature distribution at optimal motor speed is shown in figure 11. Simulated airflow patterns indicated that the motor delivered more localized and controlled cooling, directly impacting the areas with the highest thermal load.



(a) (b)

Figure 9: Temperature distribution in PCB with (a) Embedded Motor (b) Fan

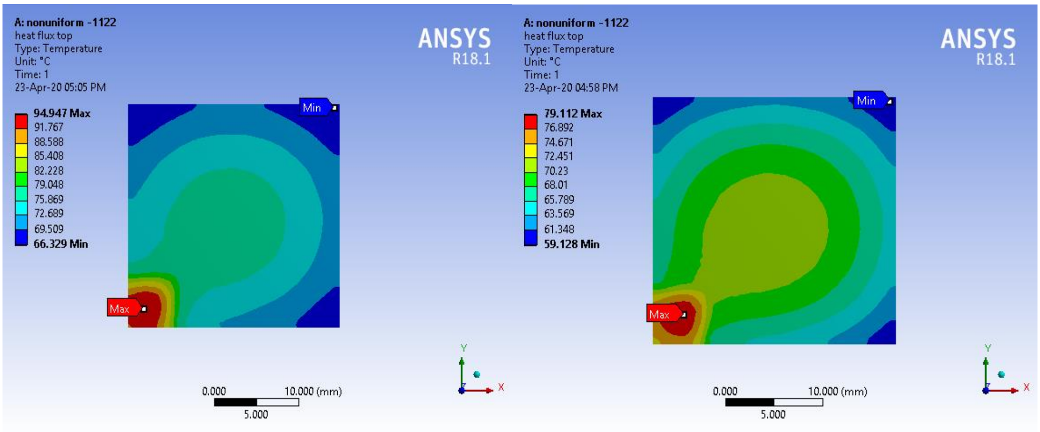


Figure 10: Temperature distribution in localized cooling and controlled cooling

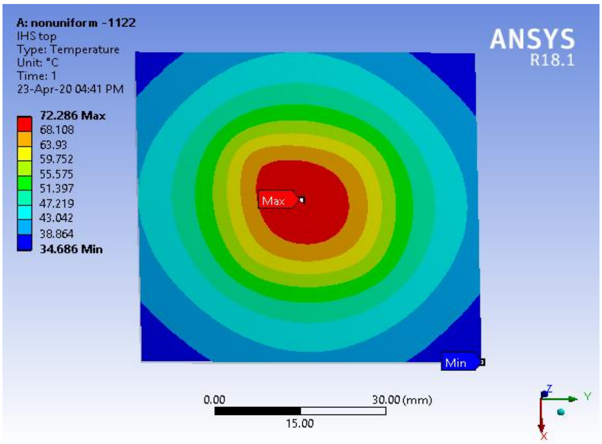


Figure 11: Temperature distribution at optimal motor speed

4.3 Power Consumption and System Integration

While the embedded motor provided significant cooling benefits, the power consumption of the motor was evaluated to assess the impact on the overall energy efficiency of the system. The motor required low power, consuming approximately 0.5-1 W, which was minimal relative to the power savings achieved by preventing overheating and improving component longevity.

The integration of the motor within the PCB allowed for an optimized, compact system that avoided the need for bulky external cooling systems. This integration simplified the design, reduced the overall size of the cooling system, and allowed for more efficient use of available space in electronic devices. Comparison of thermal resistance in PCB with Embedded motor and Fan obtained using simulated results as shown in figure12.

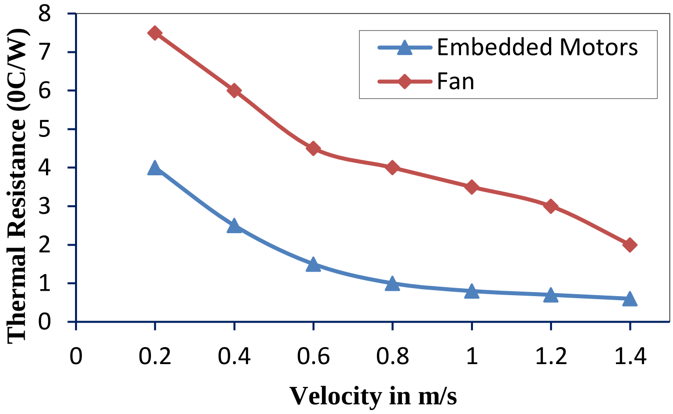


Figure 12: Variation of Thermal Resistance with Velocity

The integration of an ultra-thin PCB embedded motor offers several advantages over conventional cooling methods [22]. One of the key strengths of this approach is the compactness of the system. By embedding the motor directly within the PCB, this technique eliminates the need for external cooling solutions such as bulky fans or large heat sinks, which can add significant weight and volume to the overall design.

The active cooling provided by the embedded motor is particularly beneficial for applications where space constraints and thermal management are critical. For instance, in high-performance computing devices, such as processors and GPUs, the ability to effectively manage heat in a small form factor can significantly extend the lifetime of the components and improve system stability.

Localized cooling provided by the motor allows for targeted thermal management, which means that critical components can be kept within their optimal temperature ranges without overcooling fewer sensitive areas. This localized cooling approach not only improves thermal performance but also optimizes energy usage by preventing the overuse of cooling resources.

The efficiency of the embedded motor-based cooling system can be influenced by several factors, such as the speed of the motor, the airflow direction, and the placement of the motor within the PCB. Further research into optimizing these factors could lead to even greater improvements in thermal performance.

However, the motor noise and vibrations, although minimal, need to be considered for high-sensitivity applications, such as medical devices or precision instruments, where any disturbance could affect performance. Additionally, the long-term reliability of the embedded motor system, including potential wear and tear from mechanical components, requires further investigation.

Overall, the results demonstrate that embedding a motor into an ultra-thin PCB offers a viable, efficient solution for enhancing electronic cooling. The approach is particularly suited for applications that demand high thermal performance in compact designs, providing an innovative alternative to traditional cooling methods.

5. CONCLUSIONS

1. Enhanced electronic cooling, harnessing the potential of ultra-thin PCB-embedded motors, represents a paradigm shift in managing thermal challenges within electronic systems.

2. The system demonstrated capability to efficiently disperse heat and maintain optimal temperatures across components signifies a breakthrough, surpassing traditional cooling methods.

3. Its uniform temperature distribution and substantial reduction in thermal signatures validate its prowess in enhancing device performance and reliability.

4. This cutting-edge cooling solution not only augments operational efficiency and device longevity but also heralds a new era of sustainable and reliable electronic systems.

5. Its validated superior cooling capabilities serve as a catalyst for innovation and integration, promising a future landscape of enhanced thermal management technologies across industries and applications.

6. As the electronic cooling landscape evolves, this pioneering system sets a precedent for optimized performance, reliability, and innovation, steering electronic devices towards greater efficiency, reliability, and technological advancement.

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